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A SIMULATION STUDY OF THE LANDING-APPROACH ATTITUDE CONTROL HANDLING QUALITIES OF THE LEM USING ON-OFF RCS THRUSTER LOGIC

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
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August 26, 1963

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A SIMULATION STUDY OF THE LANDING-APPROACH ATTITUDE CONTROL HANDLING QUALITIES OF THE LEM USING ON-OFF RCS THRUSTER LOGIC

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SUMMARY

The lunar landing simulation was made using a fixed-base simulator containing pilot displays, an attitude controller, and a main engine throttle. The six-degree-of-freedom equations for the vehicle dynamics and attitude control system equations were solved by means of an analog computer.

The LEM was assumed to have a fixed installation main engine. The main engine thrust was variable and was controlled by a throttle actuated by the pilot's left hand. Fixed thrust-level reaction jets operated either full on or off provided spacecraft attitude control. Characteristics of the reaction jets such as the delay in valve actuation and lag in the thrust buildup and decay were simulated on the analog computer. Attitude control of the LEM was effected by a three-axis controller operated by the pilot's right hand.

Two attitude control systems were evaluated during the study. The first control system enabled the pilot to command rates around each of the three vehicle axes. The second was a hybrid system in that attitude was commanded about the pilot pitch and roll axes and rate commanded about the pilot yaw axis.

The results of this study indicate that the control systems investigated which utilized on-off thruster operation provided at least equally good handling qualities as similar control systems utilizing linear proportional thrusters.

INTRODUCTION

Previous studies (ref. 1, 2) have been conducted to determine the handling qualities of the LEM vehicle during the landing phase of the LEM mission. These studies involved the use of variable thrust reaction jets. The control jets that are being developed for the LEM attitude control system are constant thrust reaction jets which preclude the use of linear proportional control techniques.

The use of constant thrust reaction jets requires an attitude control system employing the principle of on-off thruster operation. It was, therefore, deemed necessary to obtain information relative to the handling qualities of the LEM vehicles having an attitude control system utilizing on-off thruster operation. The results of the previous studies provide a basis for comparison to determine if an on-off-thruster attitude control system would provide handling qualities equal to those of a system employing proportional techniques.

To provide data for this comparison, the Flight Simulation Branch of the Spacecraft Technology Division conducted a simulation study of the LEM vehicle having an on-off attitude control system. The study was confined to that portion of the lunar landing phase of the LEM mission below 1,000 feet. It is the prupose of this document to describe the simulation and the results of the study.

SYMBOLS

I_{sp}	Mean effective specific impulse
Ix_b, Iy_b, Iz_b	Principle and body moments of inertia of LEM, slug-ft^2
M	Mass of LEM in slugs
Mx_b, My_b, Mz_b	Control moments about LEM body axes
T	Control jet thrust, lb.
x_b, y_b, z_b	LEM Body axes
X_M, Y_M, Z_M	Moon axis system with center fixed on the surface of the moon. The X and Y axes are in the local horizontal plane, whereas the Z axis is parallel to the local vertical and is positive towards the center of the moon.

DESCRIPTION OF SIMULATION

General

The lunar landing simulation employing on-off thruster operation was implemented by coupling the analog solution of the six-degree-of-freedom dynamic equations to a simulated LEM cockpit. The LEM cockpit simulation included the required pilot displays, attitude controller, and main engine throttle. The equations of motion assumed a flat moon with constant gravity; that is, no orbital terms were included since the range of operation and velocities were restricted. The task to be performed was such that with the vehicle in a hover attitude at a preselected altitude the pilot was to translate to the landing area, stop all horizontal velocities and land. As a restraint on pilot technique, the total fuel available for the maneuver was limited. The computer block diagram of the simulation is shown in figure 1.

Cockpit Displays

The pilot display used during the simulation is shown in figures 2 and 3. The instruments used and their functions are as follows:

Oscilloscope.- Used to show the pilot the relative position of the landing area with respect to the LEM. The position of the LEM is at the center and the landing area is the small circle at the upper center of the scope face. Downrange distance was shown on the vertical axis and crossrange distance on the horizontal axis. Three selectable scales were incorporated in the display; 5,000, 500, and 50 feet full scale. The axis system used to measure downrange and crossrange distance is shown in figure 4.

Two-axis eight ball attitude indicator.- Presented pitch and roll attitude information. The angles were measured with respect to the moon-fixed reference system.

Heading indicators.- Presented the vehicle yaw with respect to the moon-fixed reference system.

Downrange and crossrange velocity indicator.- Presented downrange and crossrange velocities. The crosspointer meter is in the upper center of the panel. The velocities were measured in the same axis system as the downrange and crossrange distances shown on the oscilloscope. Full scale on the instrument corresponded to 300 or 30 ft/sec, depending upon the scale selected by the pilot.

Altitude and altitude rate indicator.- These parameters were presented on one instrument with two meter movements. The selectable altitude scales were 10,000, 1, 000, and 100 feet. Selectable altitude rate scales were 1,000, 100, and 10 ft/sec.

Thrust to weight meter.- Presented the relative engine thrust of the LEM to the LEM weight.

Rate indicator.- The three body rates were presented on one indicator with separate meter movements for each of the rates. The rate scale was 5°/sec per division (20°/sec in roll and yaw, 15°/sec in pitch for full scale defection). The body axis system of the LEM vehicle is shown as figure 4.

Main engine and attitude fuel.- Gave the quantity of main engine and attitude fuel in pounds. Full scale instrument deflection corresponded to 5,000 lbs. of main engine fuel and to 1,000 lbs. of attitude fuel.

Clock.- Gave time of day and elapsed time for a run.

ATTITUDE CONTROLLER AND MAIN ENGINE THROTTLE

The LEM attitude was controlled by a three-axis stick operated by the pilot's right hand. The thrust of the fixed main engine was regulated by a throttle controlled by the pilot's left hand. Figure 2 shows the attitude controller and throttle which are located on a panel below the main instrument panel.

Rotations of the attitude controller would command either an attitude or body rate proportional to the stick deflection, depending on the system being simulated. The motion of the LEM was about the same axis and in the same direction as the motion of the attitude control stick (fig. 5). The stick was spring loaded so that it would return to a zero command position upon being released. The maximum deflections of the attitude controller was ±30° for pitch and roll control and ±32° for yaw control. Equivalent linear motion at the point where the controller was gripped was about $\pm 1\frac{1}{8}$ inches for pitch and roll control motions.

The main engine thrust was proportional to throttle position. Thrust could be cut out completely by pulling the throttle back through idle. This action operated a spring-loaded microswitch.

CONTROL SYSTEM

Two types of control systems were investigated. One system commanded body rates about the three LEM axes; the other system commanded attitudes in both pitch and roll but commanded a rate about the body yaw axis. Open loop attitude control by direct actuation of thrusters was not investtigated because the comparison of control with on-off thrusters and proportional thrusters was made in reference 1.

Figure 6 shows a block diagram of one channel of the rate command system. In this system the signal from a rate gyro, which had a hysteresis of 0.02 degrees per second, was summed with a signal from the control stick to generate an error signal q_e. The gain K_2 in the circuit between the attitude controller and the summing point provided a means of adjusting the control stick command sensitivity. The error signal at the summing junction was fed to a comparator that turned the control jet on when the signal exceeded a preset deadband. The dynamic characteristics of the control jet were simulated by transfer functions which followed the comparator. The simulated control jet had a transport delay and first order lag incorporated into the thrust characteristics during both thrust buildup and decay. Figure 8 shows the thrust-time history of such a jet burning a hypergolic fuel.

The attitude command system shown in figure 7 is the same as the rate command system from the summing point to the gyros. The error signal is made up of a command signal from the attitude controller, a gimble angle from a stable platform, and a rate gyro signal modified by gyro characteristics and gain K_3. The vehicle attitude commanded was proportional to the controller position. For this study, the gain K_2 was fixed to give one degree of attitude for one degree of controller deflection.

TEST PROGRAM

Parameters Varied

The following parameters were varied during the study of the rate command system:

1. Control jet thrust - 10 to 200 lbs.
2. Switching deadband - .1°/sec to 2°/sec.
3. Stick sensitivity - $\frac{1}{6}^{\circ}$/sec/deg to $\frac{2}{3}^{\circ}$/sec/deg.
4. Rate command limit - 5°/sec to 20°/sec.
5. Center of gravity offset - 0" to 4".

The parameter variations for the attitude control system in pitch and roll were:

1. Control jet thrust - 100 and 200 lbs.
2. Switching deadband - .25 and 1°.
3. Ratio of rate gain to attitude gain - .5 and .75

4. Maximum attitude command 30°. No variation

5. Center-of-gravity offset x_b and Y_b, 0" and 2".

A rate command system was used for control around the z_b axis since the required yaw angle would not normally be zero. A maximum rate command of 20°/sec was used for all runs with the control jet thruster size and switching deadband being the same as used in the attitude command system.

Standard Control Task

To enable a comparative evaluation between the various pilots, a standard control task was followed. As has been stated earlier, the task was to translate to a landing area and land. The initial conditions of the vehicle were as follows: hover altitude, 500 feet; velocities, zero; down-range distance to landing area, 4,000 feet; and crossrange distance to landing area, 3,000 feet. The pilot was instructed to yaw the LEM directly toward the target, pitch the vehicle to obtain a forward velocity of 100 to 150 ft/sec, and simultaneously initiate a descent rate of 5 ft/sec. Between 1,000 and 1,500 feet from the landing area the LEM was to be pitched up to initiate a reduction in the forward velocity so that by the time the vehicle was within about 100 feet of the landing area the velocity would have been reduced to 10 feet per second. From this point the pilot would come to a hover and land. To place some constraint on the pilot, the translational fuel supply was limited. When the fuel was exhausted, the main engine stopped thrusting and the LEM accelerated until it struck the moon's surface.

Methods of Evaluation

The primary method of evaluation was for the subject to qualitatively rate the control system for each run in accordance with the Cooper rating system. A rating sheet (table I) was filled out by the subject at the end of each run. If possible, the subject was asked to give the rating of each system before completing a landing as the exact touchdown conditions tended to prejudice the rating of the particular system being tested. Other conditions such as fuel consumption, landing accuracy, velocities, and attitudes were recorded and examined for compatibility with the pilot rating.

Test Subject

Five test subjects flew all or part of the test program, and all test subjects received considerable practice prior to starting the test runs. One of the test subjects was a Project Mercury astronaut and three of the remaining subjects had considerable military pilot experience.

The other subject had no pilot experience but had a background of flight test engineering related to control systems.

CHARACTERISTICS OF THE SIMULATED VEHICLE

The physical characteristics of the LEM vehicle used for this study are as follows:

Mass = 455 slugs at beginning of run

I_{xx} = 9057 slug-ft^2

I_{yy} = 8860 slug-ft^2

I_{zz} = 4507 slug-ft^2

Mx_b = 11.83 x T ft-lb

My_b = 11.75 x T ft-lb

Mz_b = 20 x T ft-lb

Isp = 300 sec

Main engine
Max. thrust = 10,000 pounds

Idle thrust = 1,300 pounds

Fuel = 2,000 pounds

Attitude system fuel = 200 pounds

All control moments were assumed to be pure couples. The moments of inertia were assumed constant because previous studies had indicated that the effect of permitting them to vary as fuel was consumed during the relatively short time of the landing maneuver under consideration was negligible. The mass was changed as a function of fuel used because of the effect it had on translation and hover performance.

DISCUSSION OF TEST RESULTS

Rate Command System

Four independent parameters were varied during the study of the rate command system. The effect of each parameter on the control system was as follows:

Control Jet Thrust.- Control jet size proved to be an important parameter. Control jet size is a direct indication of the angular acceleration capability around each of the body axes as indicated in the section "Characteristics of the Simulated Vehicle". Figures 9a, 9b, and 9c show the effect of control jet size on pilot rating. As the control jet thrust level was increased, the numerical rating of the system decreased indicating an improved system. The curve flattens out above a control jet size of 100 lbs., indicating that very little is to be gained from the standpoint of pilot acceptance and control by further increases in thruster size. Figure 10 shows the effect of thruster size on attitude fuel consumption. Attitude fuel consumption was a minimum for the smallest control jet thrust sizes and increased as thrust level was increased to 100 pounds. For the 200 pound control jets (the highest thrust level tested), however, the fuel consumption again decreased. This was attributed to the precise control the pilot had over the LEM with the 200 lb. jets.

Switching Deadband.- As in the case of control jet thrust, the size of switching deadband associated with the Comparator or thruster on-off logic box (fig. 6) had an appreciable effect on pilot rating. Figures 11a and 11b show that the pilot ratings of the control system improved as the deadband was decreased. Attitude fuel consumption was generally increased by decreasing the switching deadband except that with the 200 lb. control jet the attitude fuel consumption decreased as switching deadband decreased (fig. 10). It appeared that a 0.25°/sec. deadband would be a logical trade-off between pilot performance and fuel consumption.

Stick Sensitivity.- The stick sensitivity was directly related to the maximum rate command chosen for any system. This was because constant control stick deflections were used during this study. Figures 12a and 12b show pilot rating as function of the maximum rate that could be commanded with the 200 pound control jets simulated. The stick sensitivity can be found by dividing the maximum rate by 30° in pitch and roll and by 32° in yaw. During the runs made for this study, maximum rate was seldom commanded by the pilots. The curves in figures 12a and 12b show that for the larger switching deadband (1 deg/sec) a maximum available rate command of 10 deg/sec was about optimum, whereas for the smaller switching deadband (.25 deg/sec) the ratings indicated that a maximum available rate command of 20 deg/sec was considered just as satisfactory as 10 deg/sec.

Center of Gravity Offset.- The center-of-gravity was offset from the thrust centerline in both the LEM x_b and y_b axis. This resulted in pitch and roll moments, the magnitude of which depended on the main engine power setting. Figures 13a and 13b show the effect of center-of-gravity offset on pilot rating with variations in control jet thrust and switching deadband. The rating of any particular system usually deteriorated slightly from the same system without the offset (compare figures 12a, 12b with figures 13a, 13b), although there were exceptions which indicated the reverse. The difference in pilot rating was seldom greater than $\frac{1}{2}$ of a rating point and no significance is attached to these exceptions. The best system with no center-of-gravity offset (100 to 200 pound control jets, 0.25°/sec deadband, 10°/sec maximum command rate) would still appear to be best with the center-of-gravity offset. The disturbing moments caused by the center of gravity offsets did not present a difficult control problem as long as adequate control power was available. The test subjects considered the control power adequate when the available torque was about 400 percent of the disturbing torque about any axis. This is in agreement with the results of reference 2.

Attitude Command System

An attitude command system was used in the pitch and roll axis and a rate command control system in the yaw axis for this phase of the lunar landing study. The results of varying various control parameters are described below:

Control Jet Thrust.- A control jet thrust of 200 lbs. proved to be 1 to 2 rating points better than a 100 lb. thrust system. The best system was rated as "good, pleasant to fly" (Cooper Rating 2). Figure 14 shows the attitude fuel consumption as a function of control jet thruster size. As in the rate command system, control with the 200 lb. thrusters used less fuel than the 100 lb. system.

Switching Deadband.- There was no real agreement about which switching deadband resulted in the better control system. One subject thought the 1 degree switching deadband was best while another believed .25 degree was better. A third subject could not tell any difference.

Ratio of Rate Gain to Attitude Gain.- A ratio of rate to attitude gain of .75 rated one point lower (better) than a ratio of .5. This was because large changes of attitude were commanded relatively frequently. Commands as large as 30° were essentially attitude steps and the ratio of

.75 provided damping with only one visible overshoot. The higher ratio also reduced the limit-cycle amplitude.

Center of Gravity Offset.- The effect of offsetting the center of gravity was to make the control system seem overdamped when rotating in one direction and underdamped in the other. Attitude fuel consumption was also doubled with the center of gravity offset two inches from the thrust centerline.

Touchdown Statistics.- In addition to evaluating the handling qualities of the control system, the pilots were to land the LEM at designated spot in a vertical attitude with zero angular rates and zero longitudinal and lateral velocities. Vertical rate of descent during the maneuver was to be 5 ft/sec. The results of fifty runs are presented in a series of bar charts in figures 17 through 25. These charts present the percentage of runs that fall within specific areas of attitudes, angular rates, distances from landing area, and velocities at touchdown. The runs were made with the parameter variations as noted in the Test Program section of this report.

The pilot was able to reduce all angular rates and linear velocities except altitude rate to the required values for a majority of the runs. The spread of altitude rate from the target rate of 5 ft/sec is not large; however, touchdown velocity was less than 8 ft/sec in approximately 57 percent of the runs. It is quite possible that if the target touchdown velocity had been zero rate, a majority of the touchdown velocities would have been below 5 ft/sec.

The distance errors from the landing points were small with most being less than 25 feet. The downrange and crossrange velocities were normally below 2 ft/sec, the attitudes below 1 degree, and the rotational rates less than 1°/sec. The ability of the pilot to zero all the angular rates and velocities was probably limited as much by the display as by the control system. There is no apparent correlation between the end conditions and control system parameter variations of this study.

Comparison of Control System Utilizing On-Off and Proportional Thrusters

Rate Command.- The control response of the simulated LEM utilizing the on-off thruster logic had no peculiarities that the subject could identify with the type of control system. The general characteristics had no detectable difference from the proportional control system utilized in reference 1 and 2. The attitude response with a given size control thruster was, however, more rapid with the on-off thruster operation than with proportional thruster. This was because the on-off thruster operation utilized the full angular acceleration capability of the thruster until the desired rate was reached, whereas the system using proportional thrusters provided for an exponential approach. The "equivalent time constant" parameter that is described in reference 2 does not provide a completely satisfactory basis for comparison in that a nonlinear system such as one using on-off thruster logic will reach the commanded value of rate in approximately $1\frac{1}{2}$ "equivalent time constants" whereas a proportional system requires about 4 time constants to reach the commanded value.

Because the present study was limited in the range of control system parameters, a comprehensive comparison of the handling qualities evaluation using on-off thrusters cannot be made with the results of reference 1 and 2. Figures 15a and 15b do, however, present a few data points from the present tests plotted on a portion of a figure from reference 2, and allow a limited comparison. The figure shows that with deadband values of about $\frac{1^\circ}{4}$/sec the satisfactory region of control response characteristics is greater than that of reference 2. It appears that maximum rate commands as low as 5°/sec are satisfactory when associated with an equivalent time constant of 0.1 sec. For a maximum rate command of 20°/sec the present tests indicated a "satisfactory" rating (pilot rating of $3\frac{1}{2}$) at a time constant of about 2.0 sec compared with 1.1 seconds of reference 2. The results indicate that with on-off operation and deadbands of $\frac{1^\circ}{4}$/sec the satisfactory region of control is somewhat more extensive than that found in reference 2. As the deadband is increased (note the 1°/sec data points in fig. 15b) the satisfactory region is decreased to where it is about the same or less as reference 2.

Attitude Command.- The present tests indicated that the handling qualities evaluation of the attitude command system would be essentially the same as that of reference 2.

CONCLUSIONS

The simulation study of the LEM vehicle employing an on-off attitude control system generated data from which the following conclusion can be made:

> A control system can be designated using fixed thrust control jets having handling qualities at least equal to those provided by a linear proportional control system.

REFERENCES

1. Hill, J. A.: "A Piloted Flight Simulation Study to Define the Handling Qualities Requirements for a Lunar Landing Vehicle". North American Aviation, Inc. Columbus Division, Columbus, Ohio. Report No. NA 62H-660, Sept. 13, 1962.

2. Cheatham, D. C., and Moore, T. E.: "Study of the Attitude Control Handling Qualities of the LEM During the Final Approach to Lunar Landing". NASA, Project Apollo Working Paper No. 1074, May 10, 1963.

TABLE I.- PILOT OPINION RATING FORM

Pilot__________ Date__________ Series__________

Pitch__________ Roll__________ Yaw__________

Run	Time to Hover	Pilot Rating Attitude	Pilot Rating Translation

FLYING QUALITIES RATING

1. Excellent, Includes Optimum
2. Good, Pleasant to Fly
3. Satisfactory, but with some mildly unpleasant characteristics
4. Acceptable, but with unpleasant characteristics
5. Unsatisfactory for normal operation
6. Acceptable for emergency condition only[1]
7. Unacceptable even for emergency condition[1]
8. Unacceptable - dangerous
9. Unacceptable - uncontrollable
10. Motions possibly violent enough to prevent pilot escape

[1]Failure of a stability augmenter

Comments__________

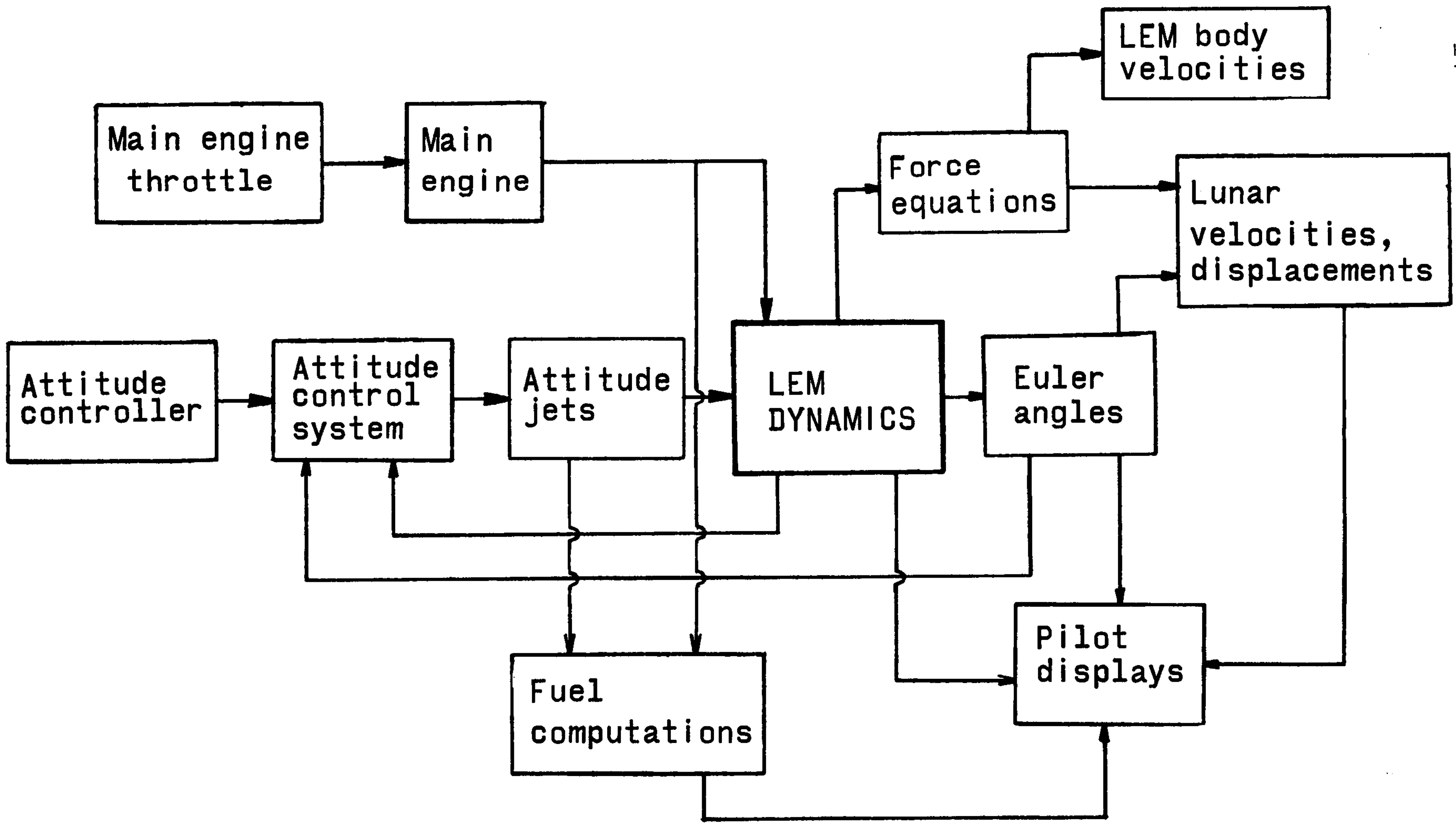


Figure 1.- Flow chart of simulation.

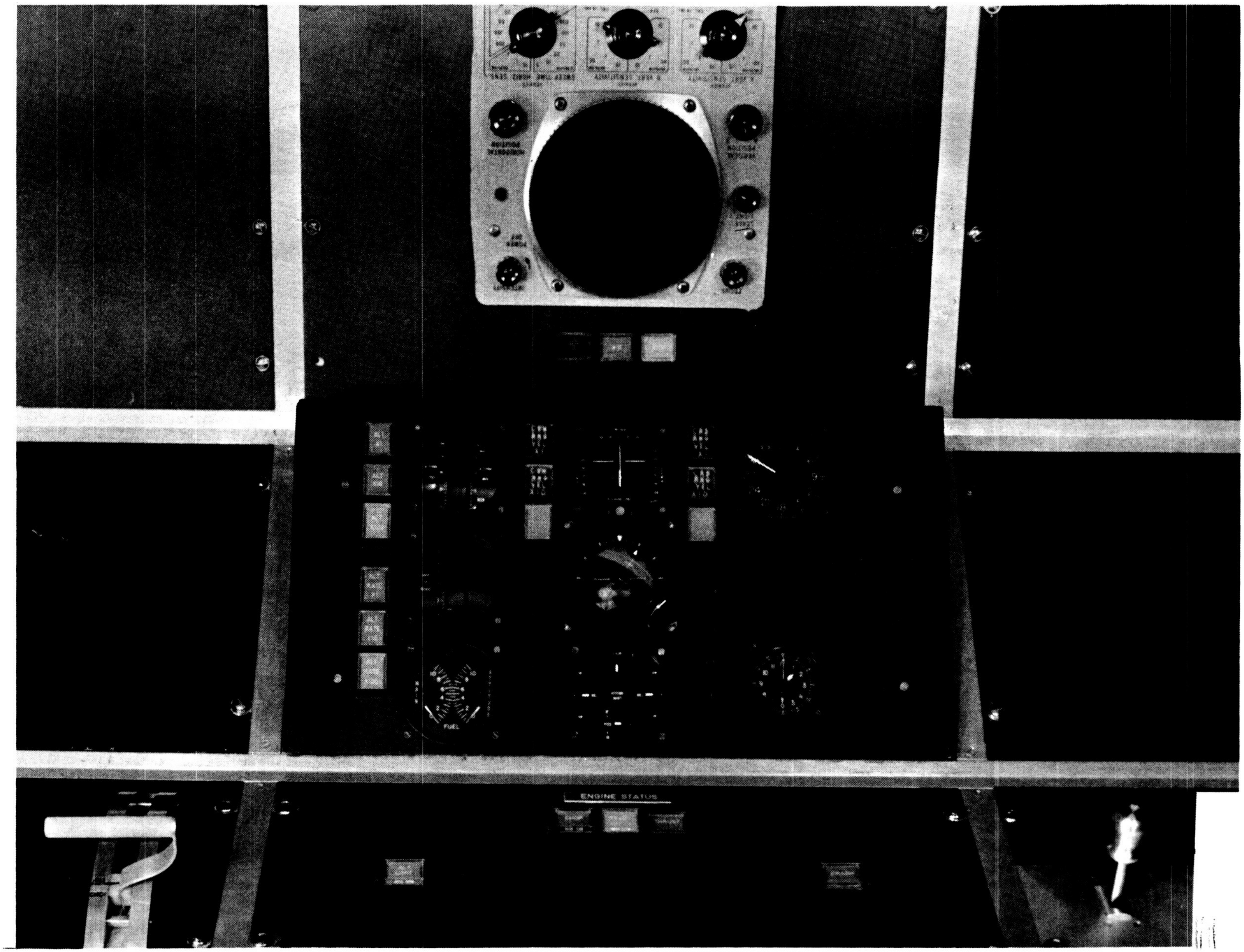


Figure 2.- Lunar landing vehicle simulator control station.

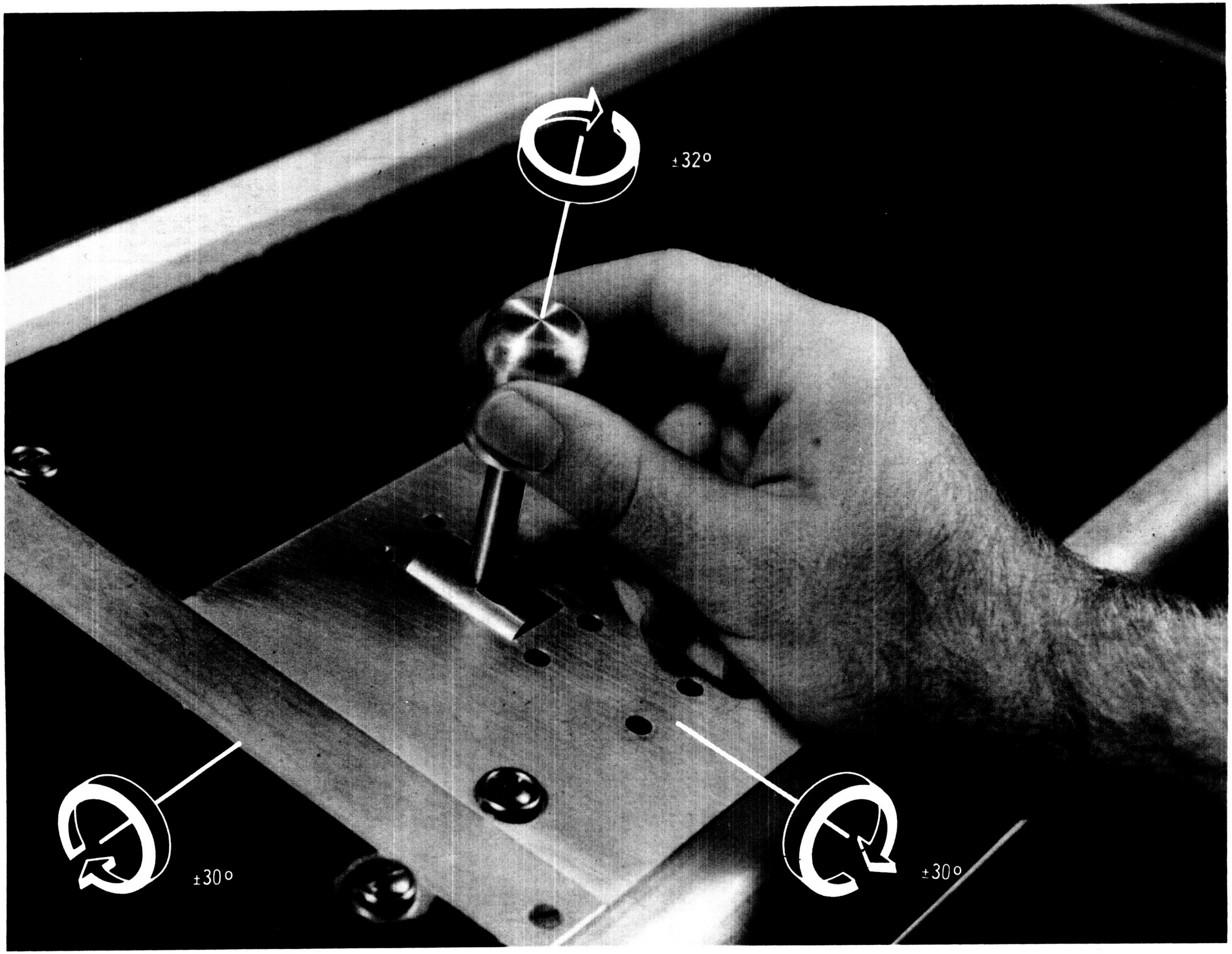


Figure 3. Hand controller motions

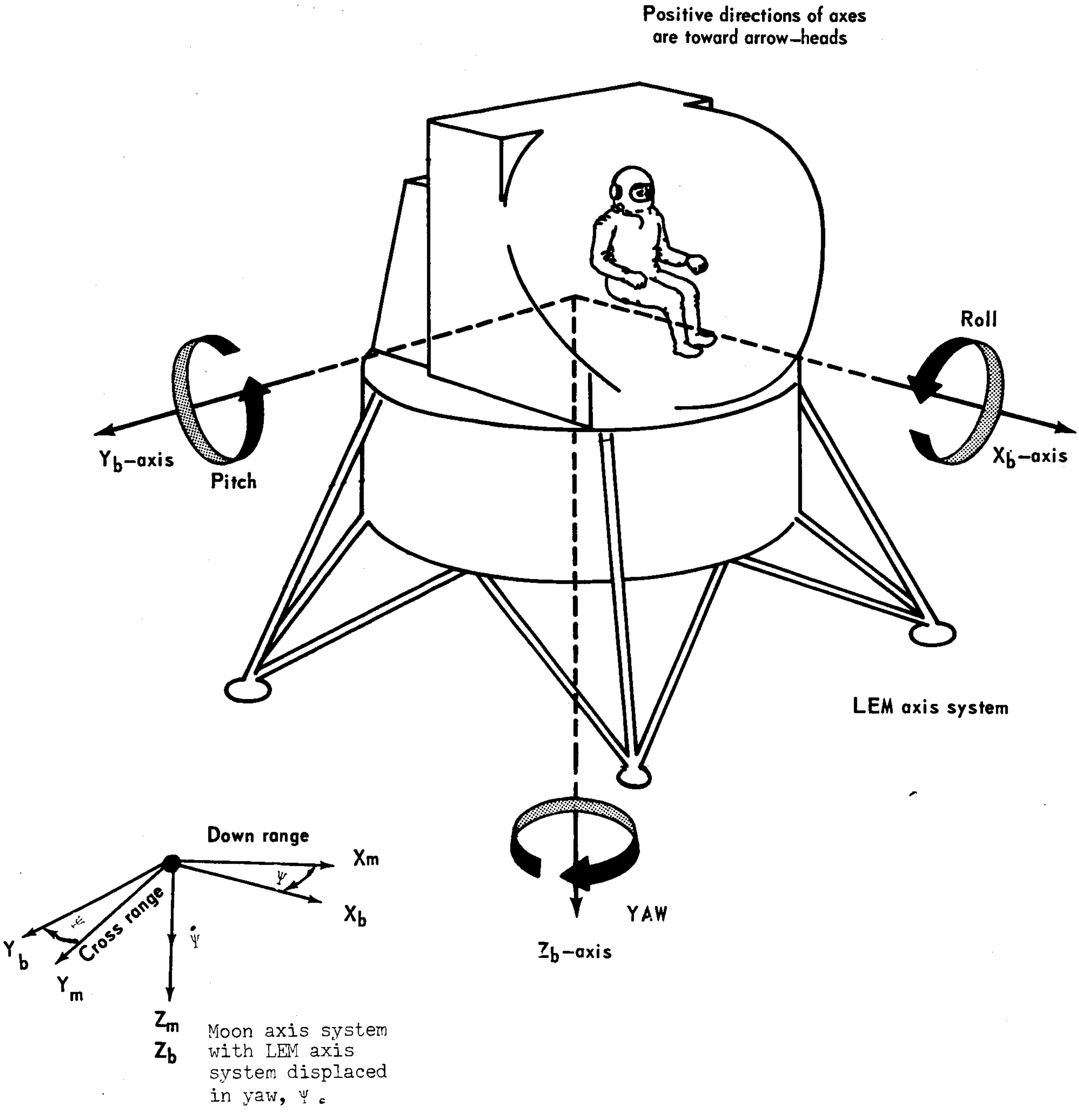


Figure 4 - Definition of LEM and moon coordinate systems

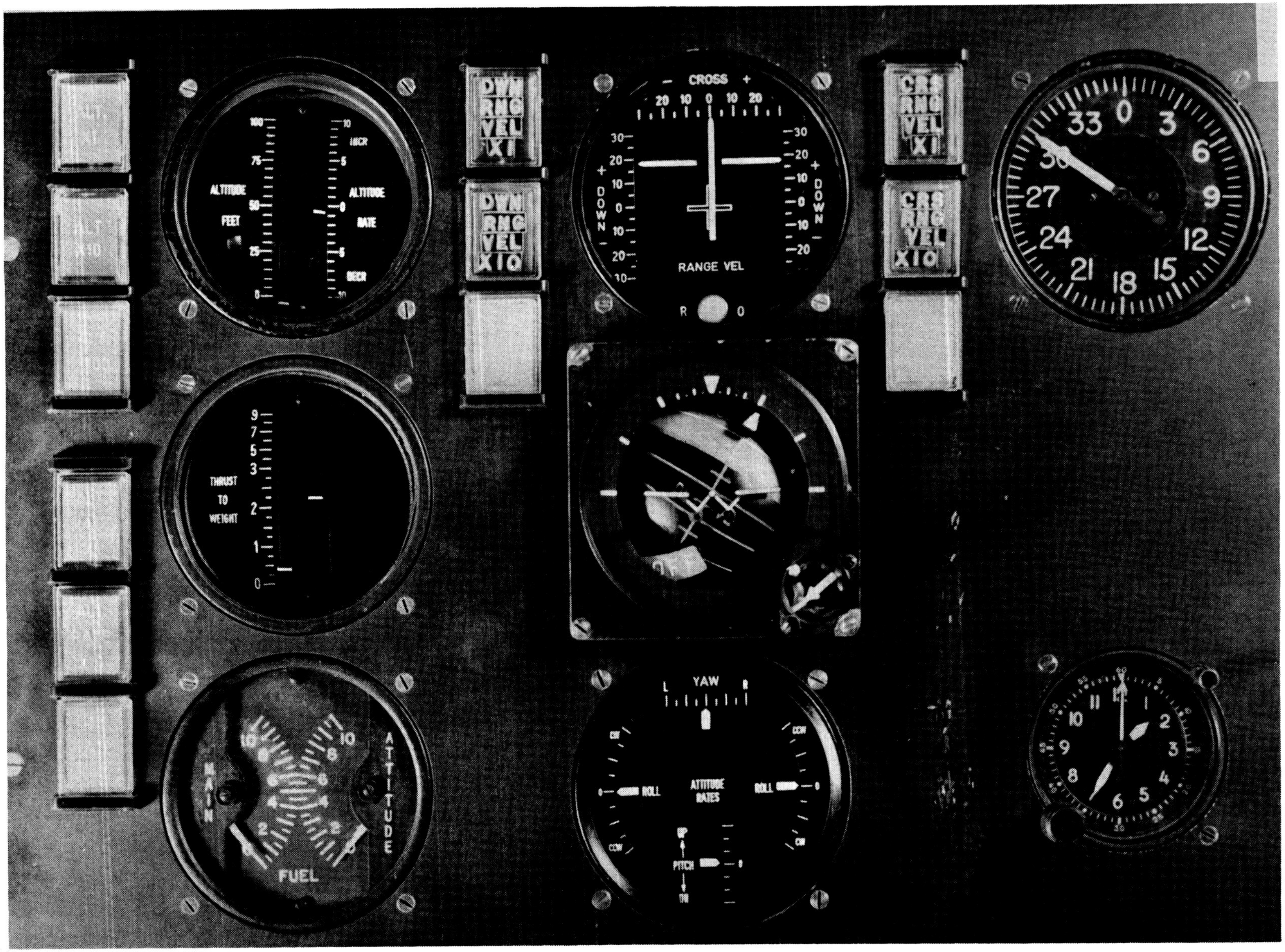
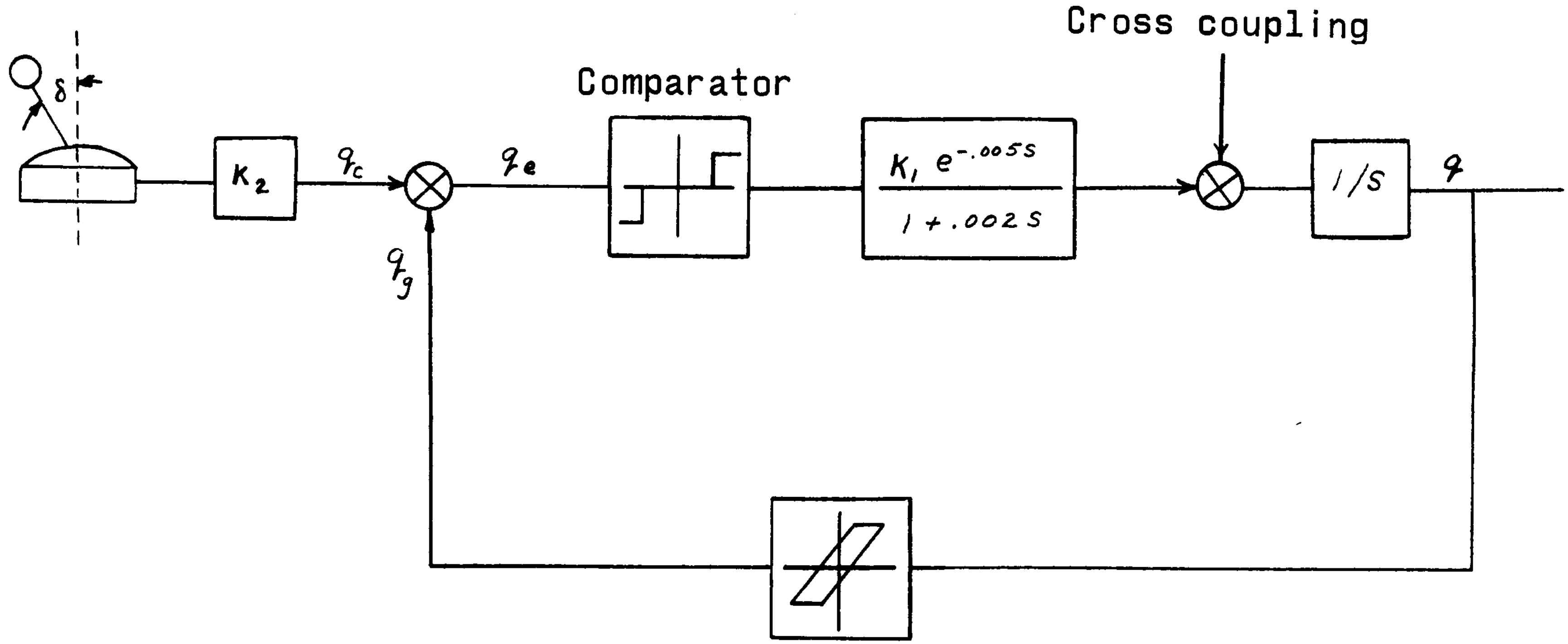


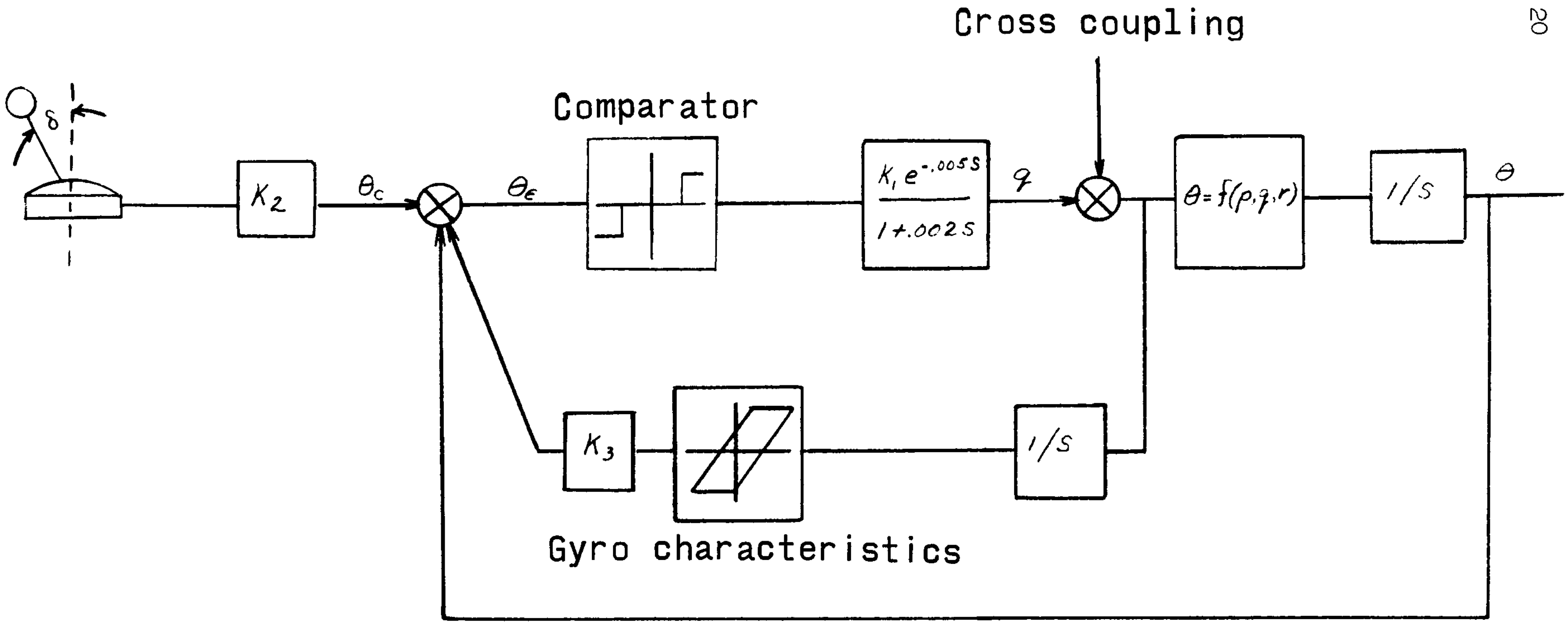
Figure 5.- Lunar landing vehicle simulator instrument panel.



K_1 - Angular acceleration

$K_2 = q_c/\delta$

Figure 6.- Rate command system, block diagram of pitch channel.



K_1 - Angular acceleration
$K_2 = \theta_c/$
$K_3 = q/\theta$

Figure 7.- Attitude command system, block diagram of pitch channel.

Typical pulse wave form

① Solenoid valve signal initiation
② Solenoid valve starts to open
③ Solenoid valve full open
④ Rise to 90% rated thrust
⑤ Solenoid valve signal termination
⑥ Solenoid valve commences to close
⑦ Solenoid valve full closed
⑧ Decay to 10% rated thrust

Attainable intervals

Interval	Duration (sec)
1-2	0.004
2-3	.003
3-4	.003
5-6	.003
6-7	.003
7-8	.004
1-4	.010
5-8	.010

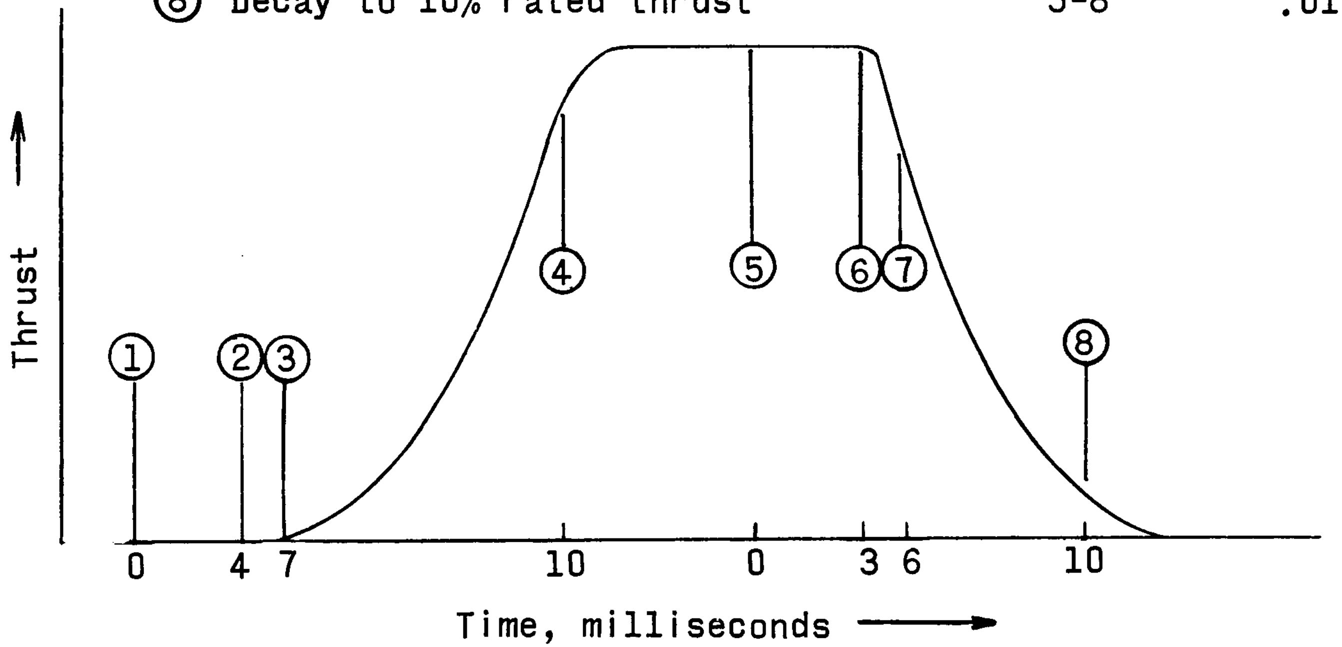
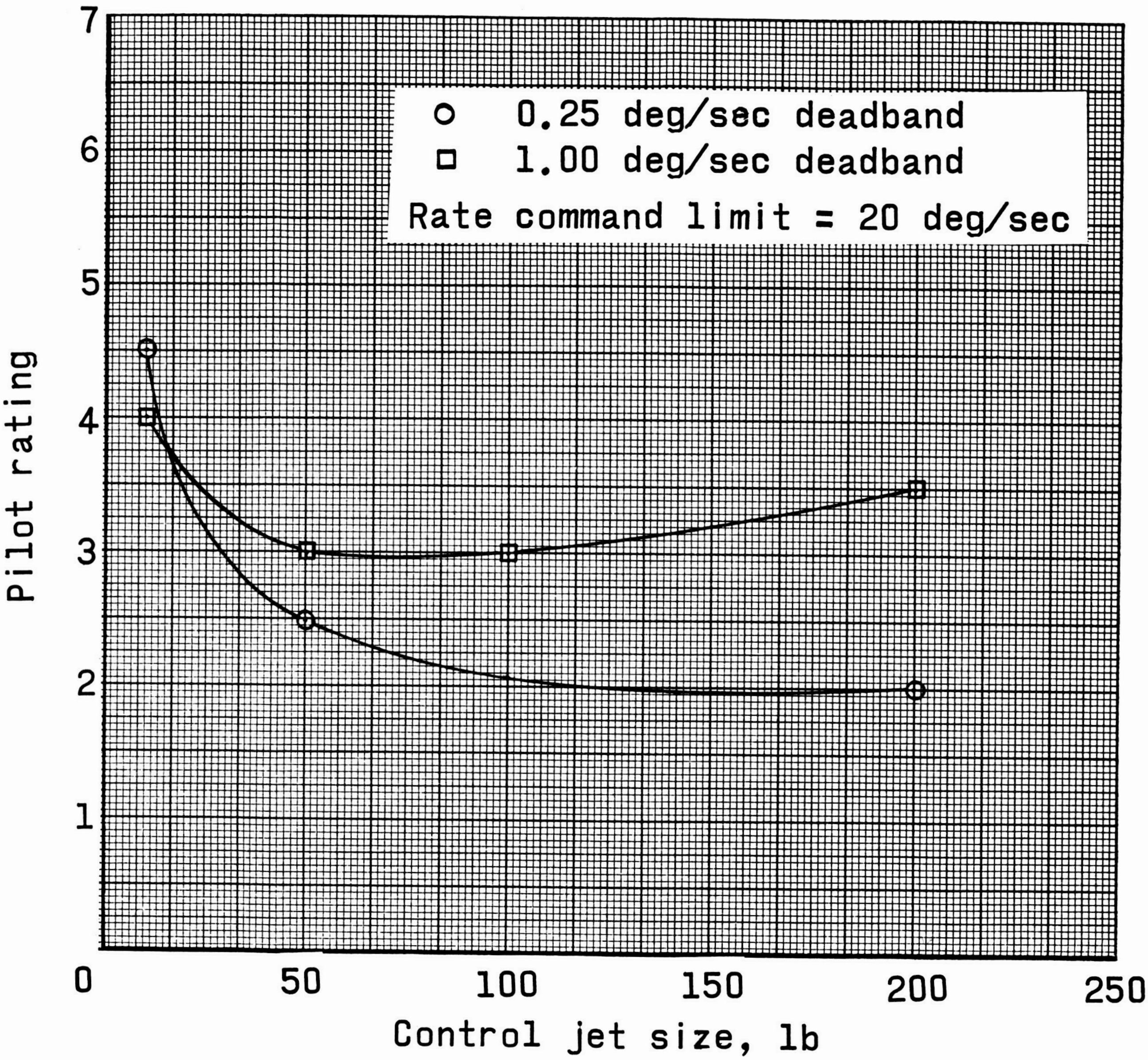
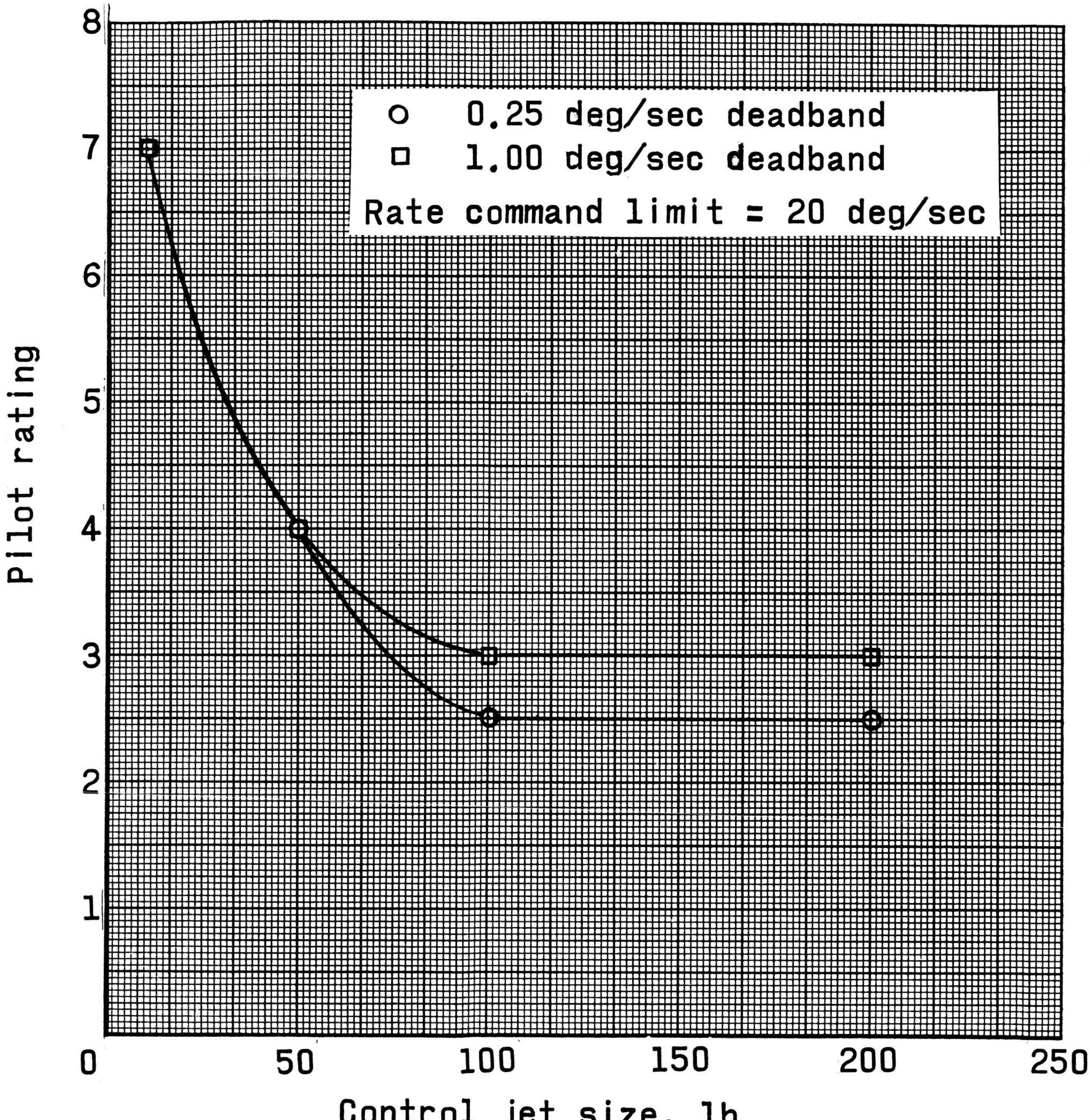


Figure 8.- Typical wave form during control jet firing. (Note that the time scale is distorted to show engine delay and lag.)



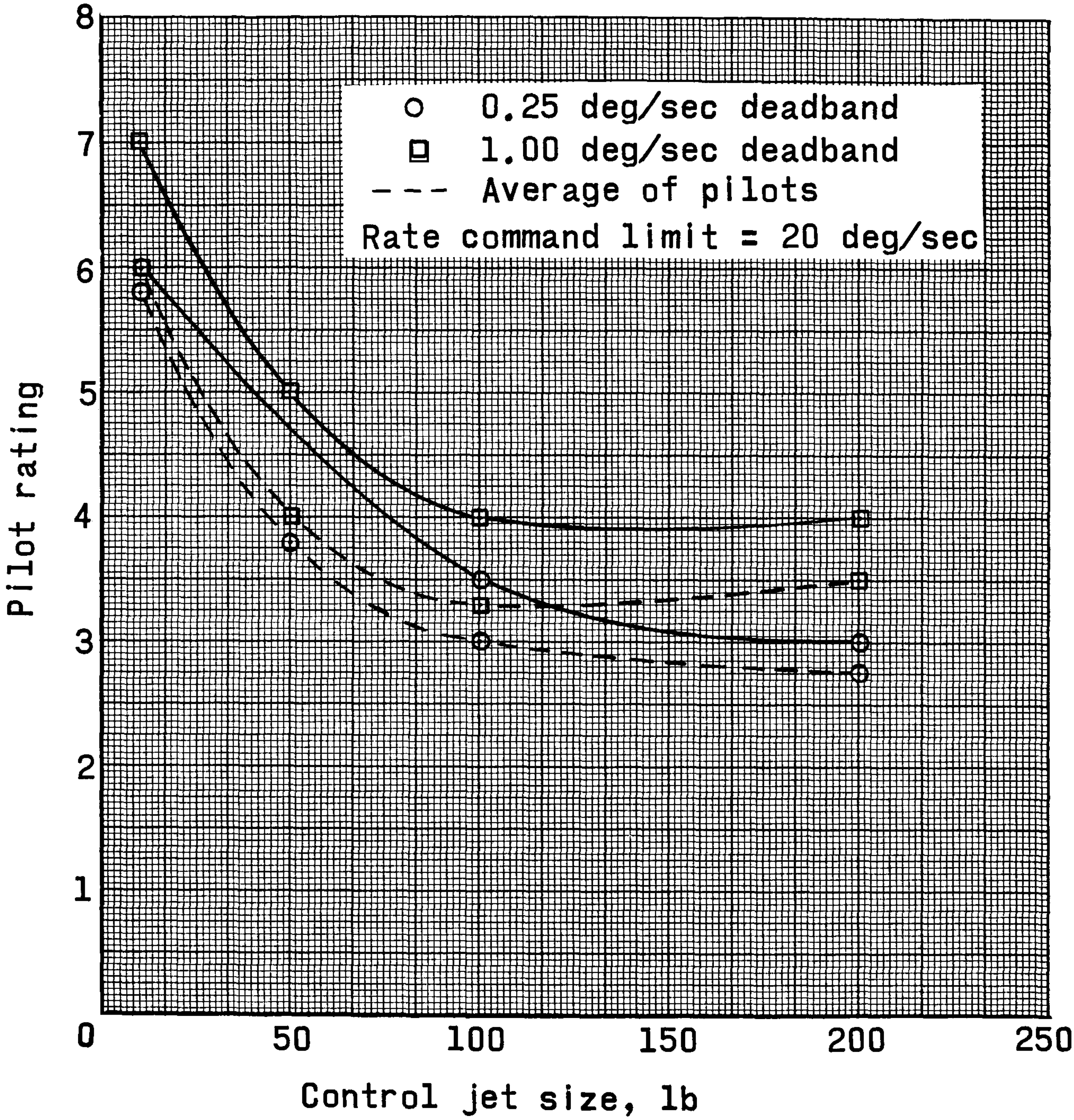
(a) Pilot No. 1.

Figure 9.- Variation of pilot rating as a function of



(b) Pilot No. 2.

Figure 9.- Continued.



(c) Pilot No. 3.

Figure 9.- Concluded.

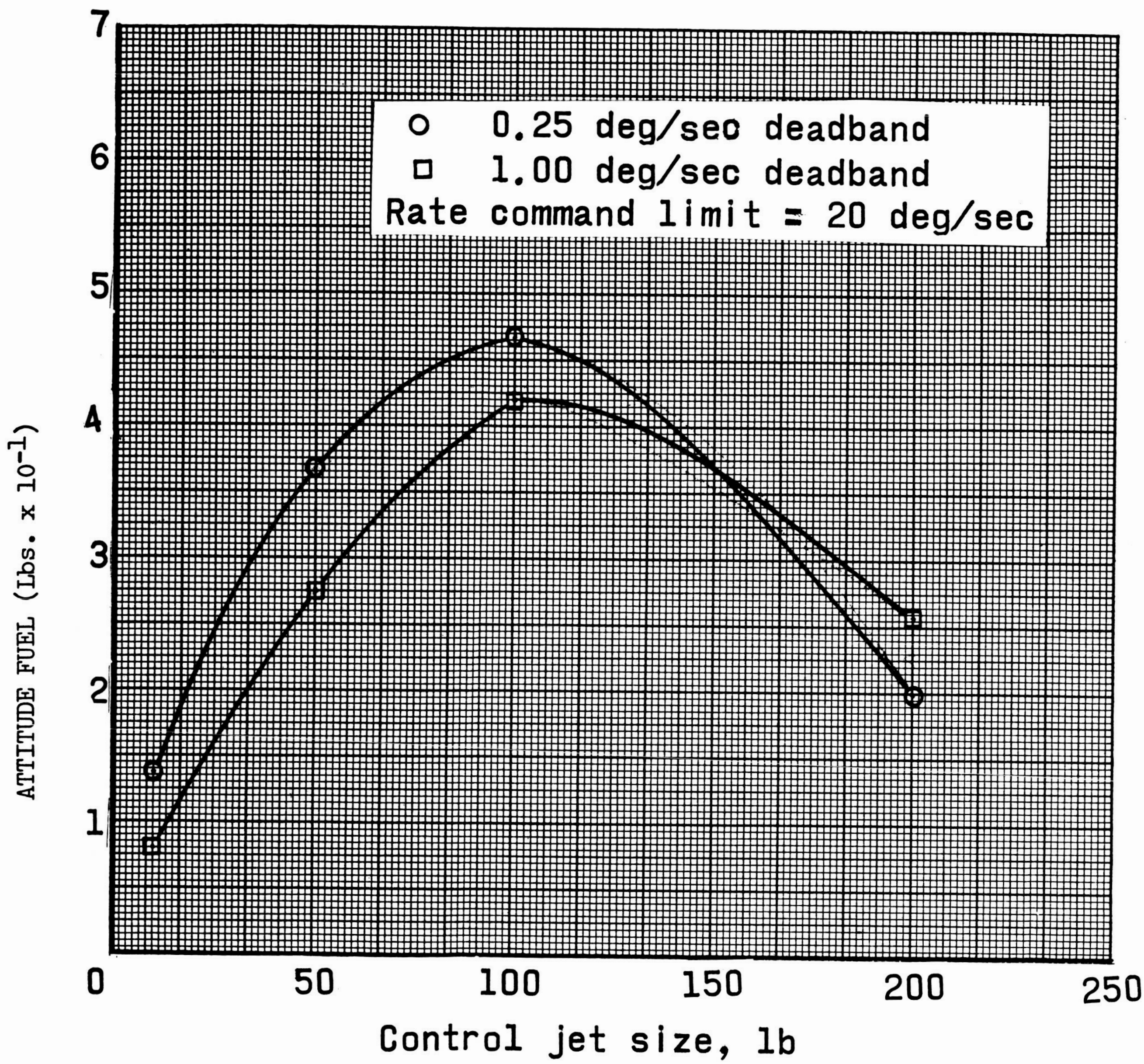
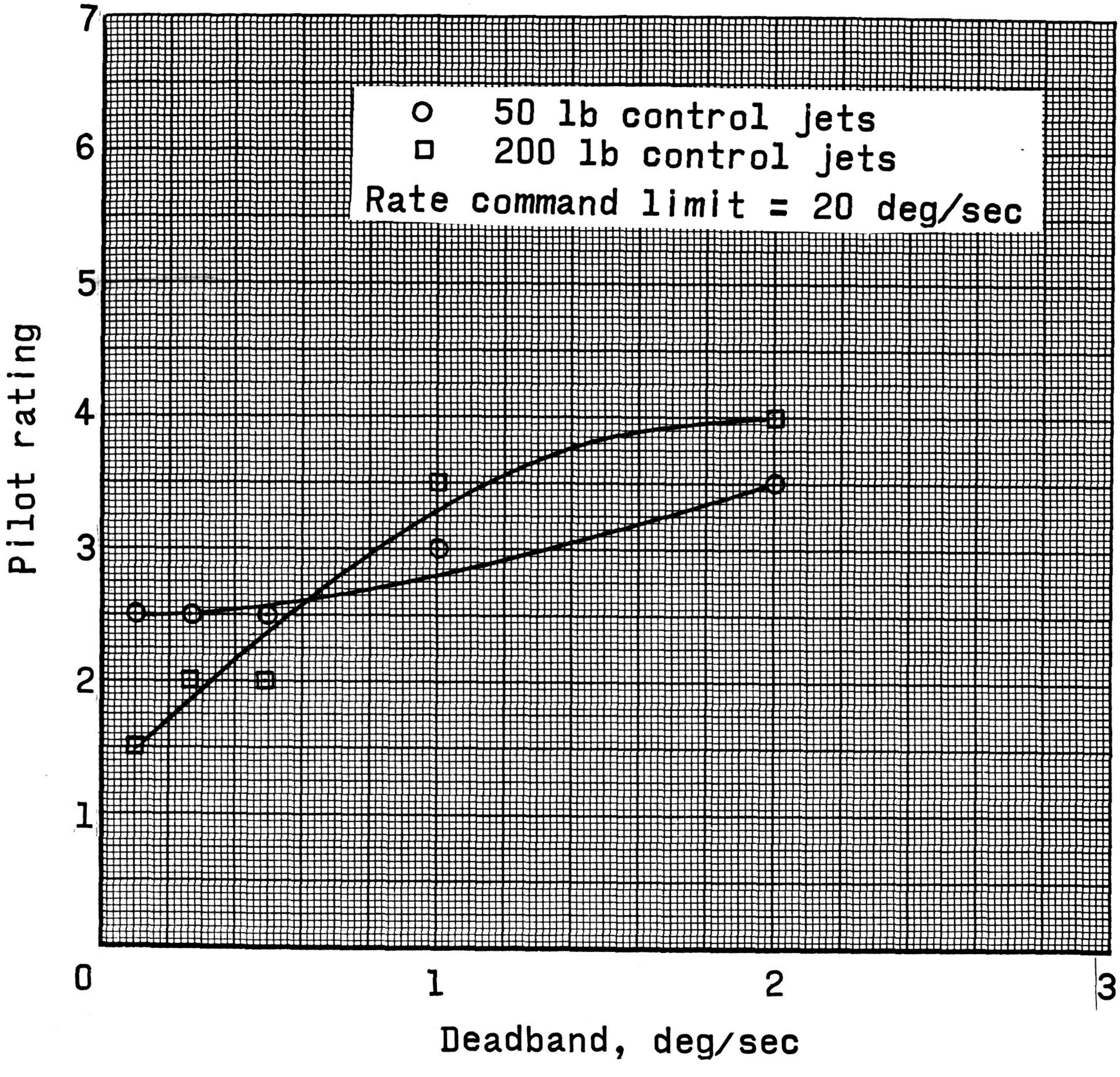
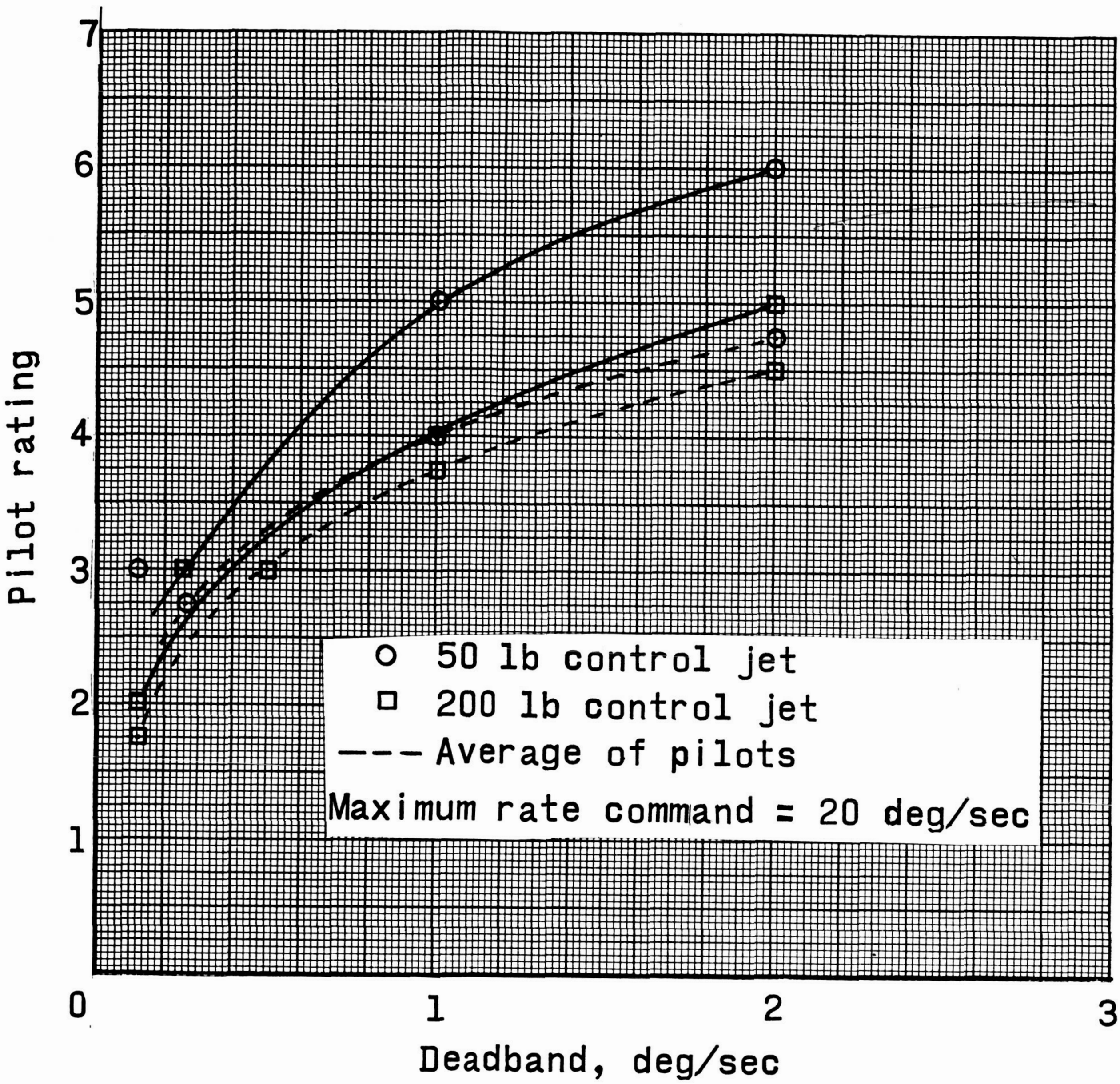


Figure 10.- Variation in attitude fuel consumption as a function of control jet size and deadband on a rate command system. Pilot No. 1.



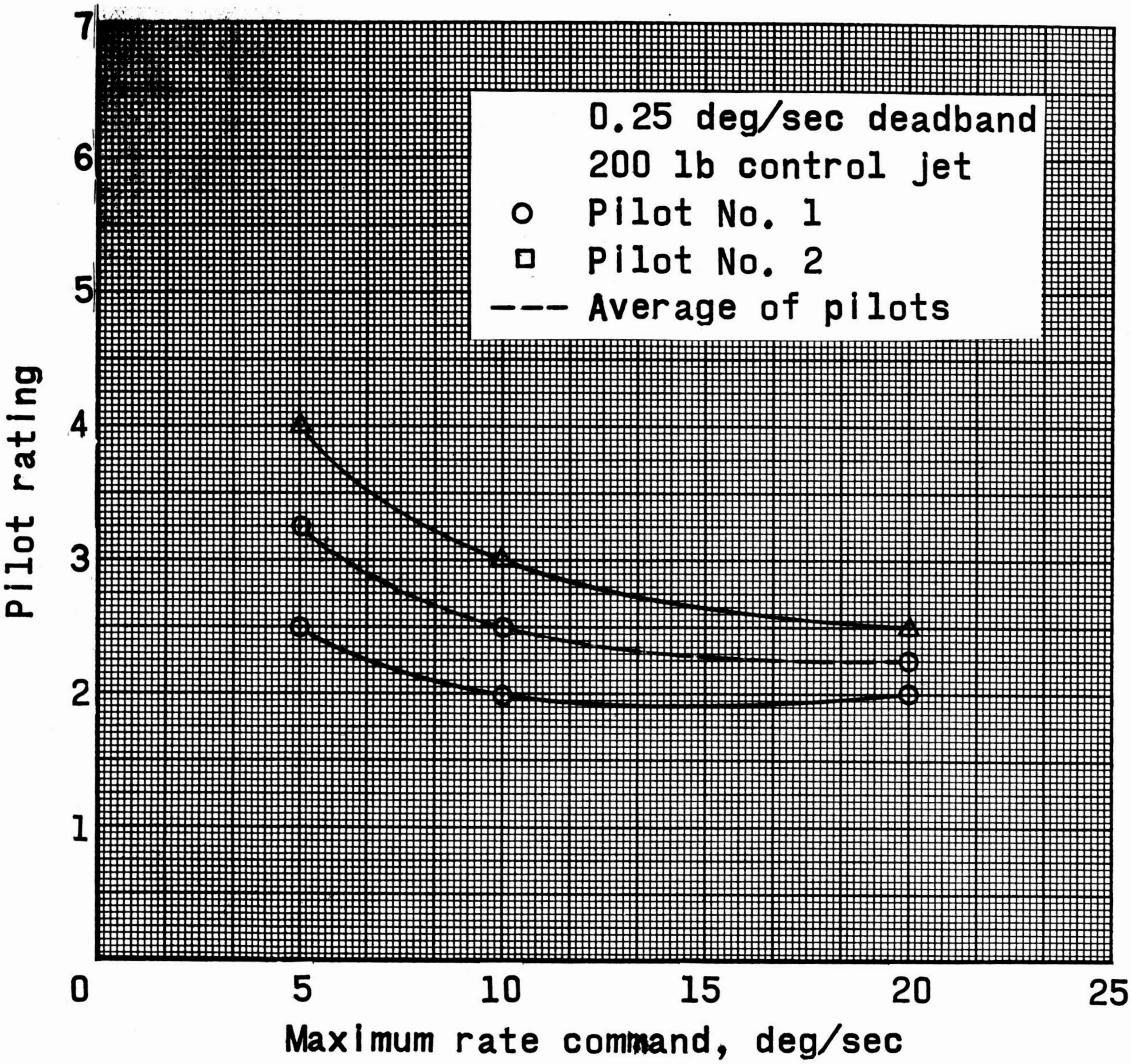
(a) Pilot No. 2.

Figure 11.- Variation of pilot rating as a function of switching deadband for a rate command system.



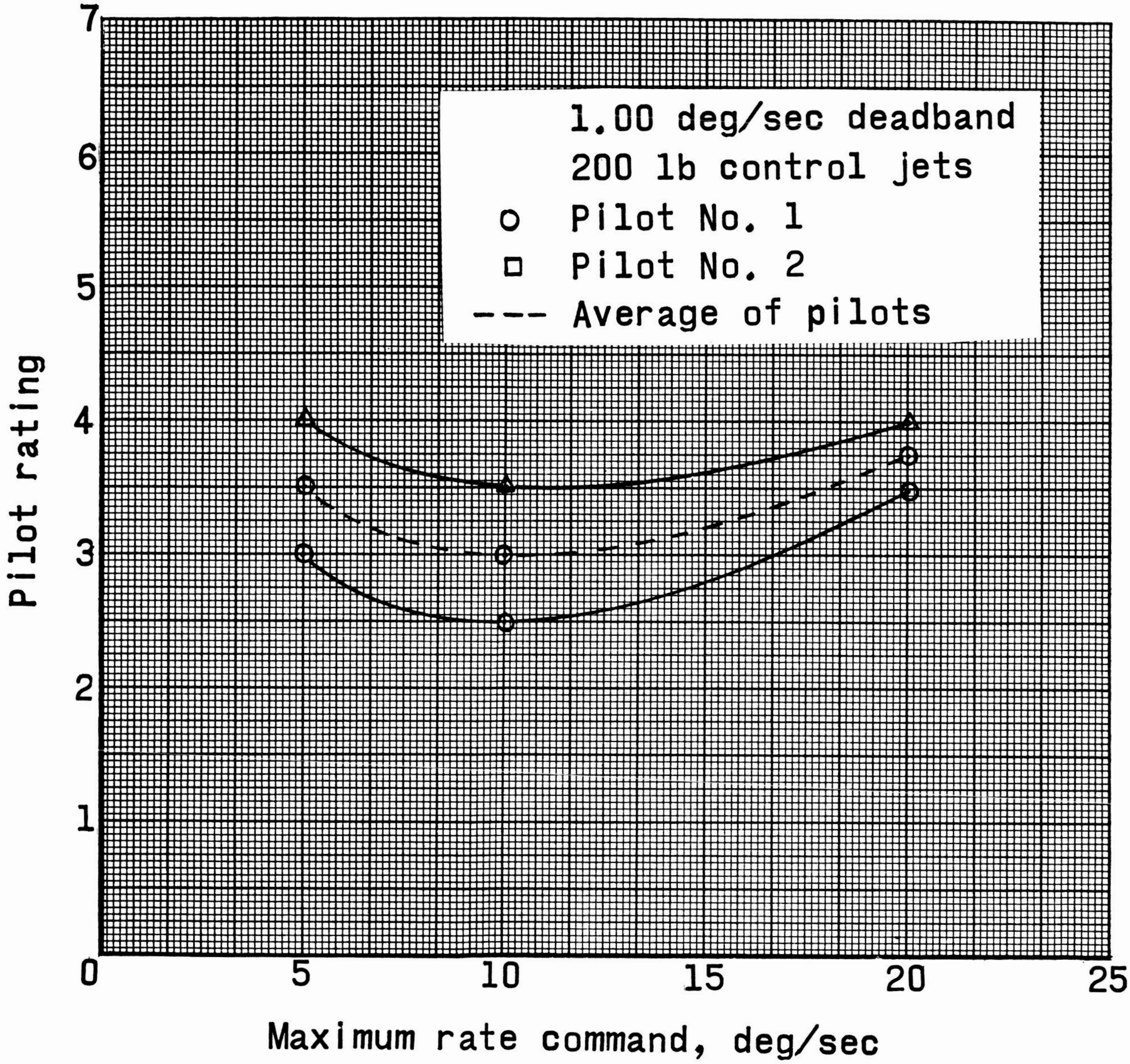
(b) Pilot No. 4.

Figure 11.- Concluded.



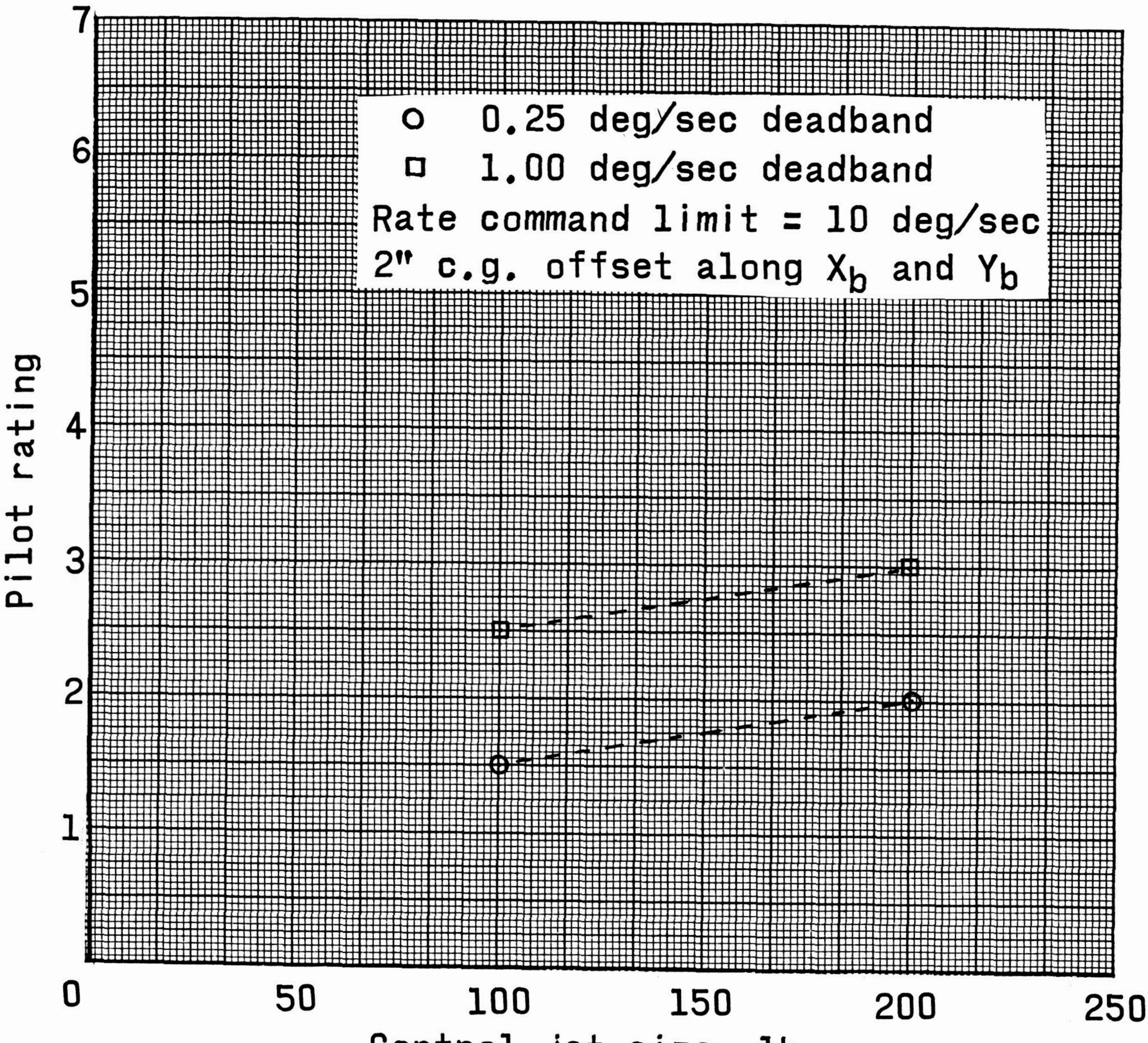
(a) 0.25 deg/sec deadband.

Figure 12.- Variation in pilot rating as a function of maximum rate command.



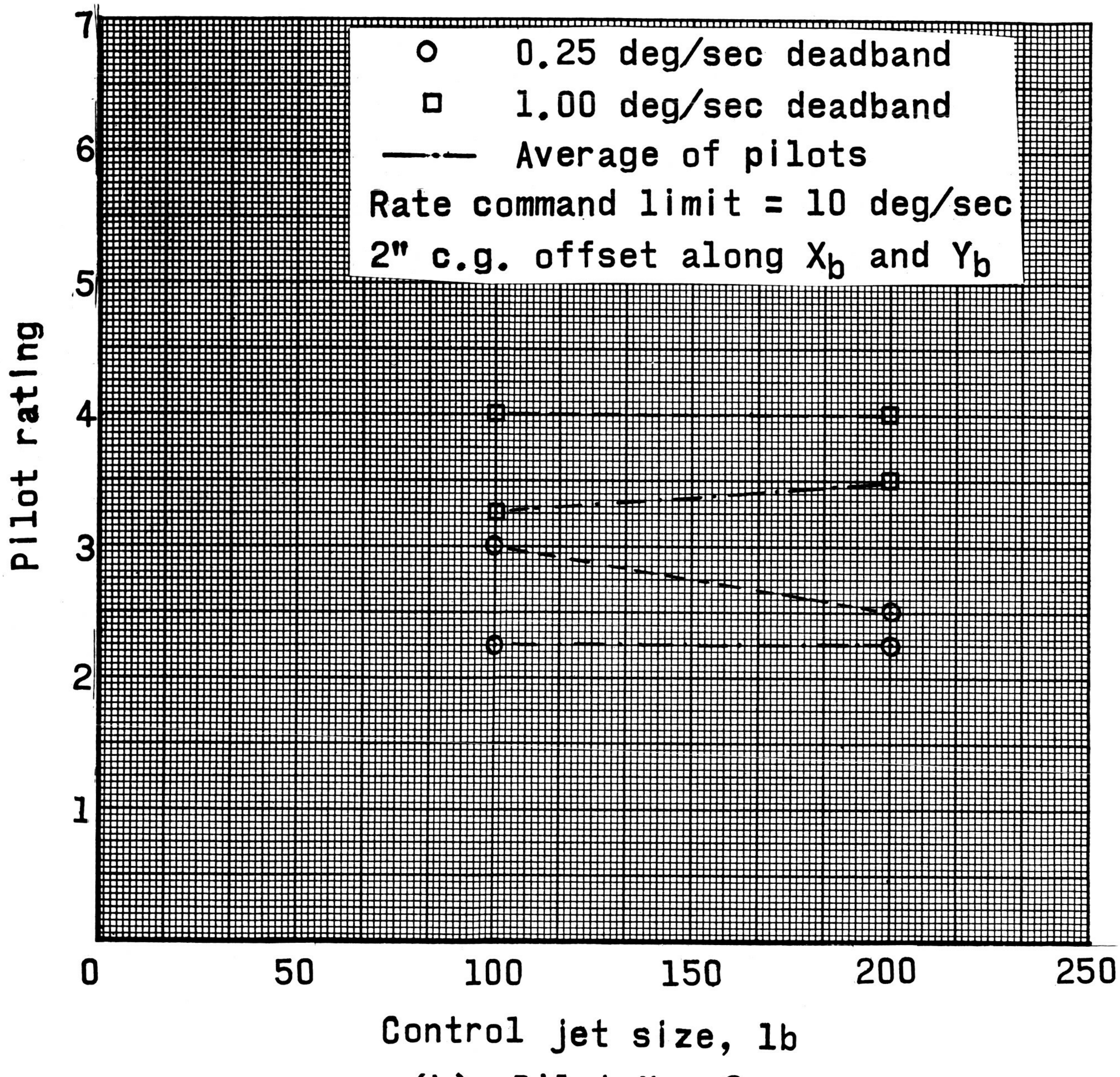
(b) One deg/sec deadband.

Figure 12.- Concluded.



(a) Pilot No. 1.

Figure 13.- Variation in pilot rating as a function of control jet size for a rate command system with a c.g. offset.



(b) Pilot No. 2.

Figure 13.- Concluded.

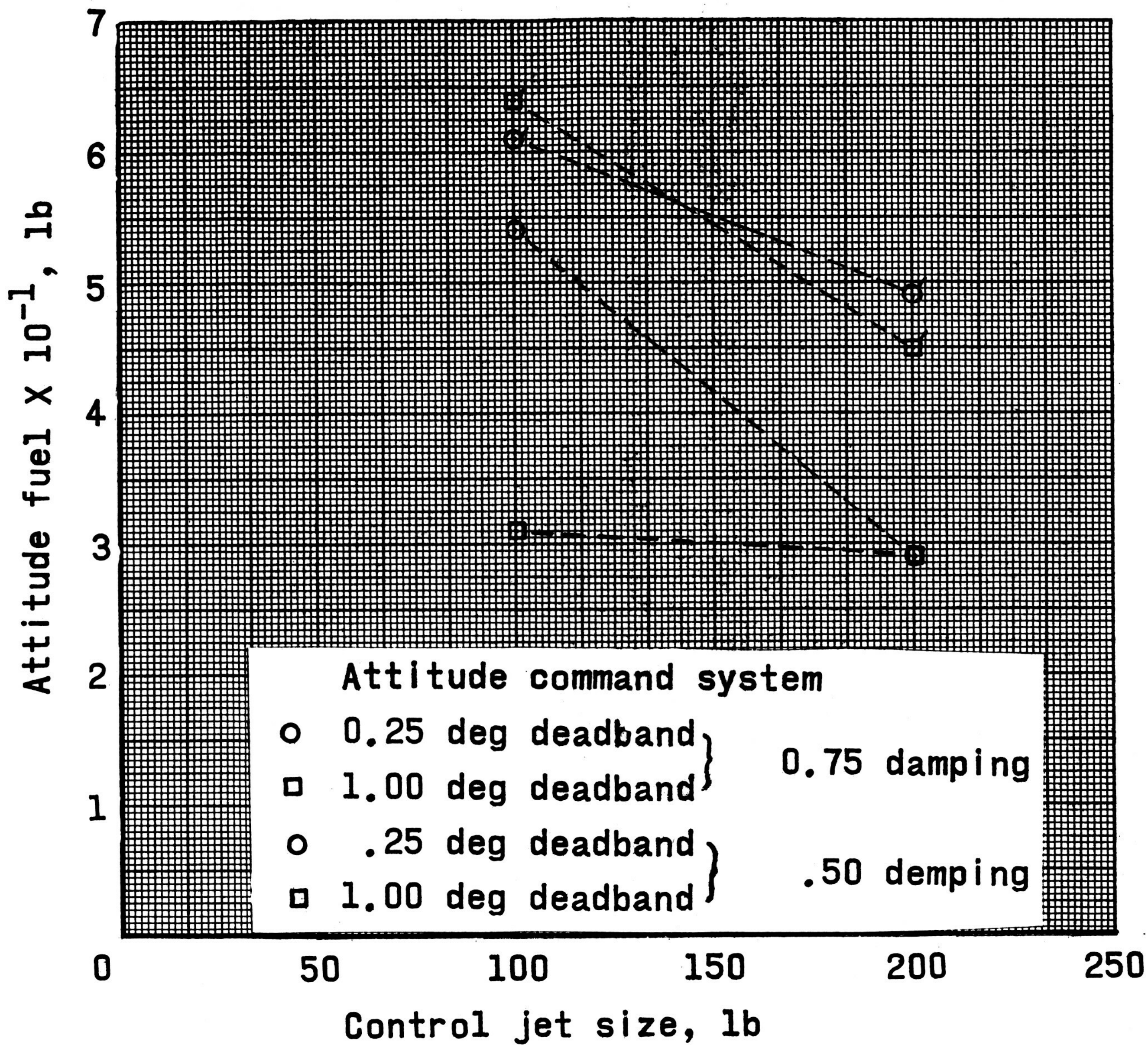
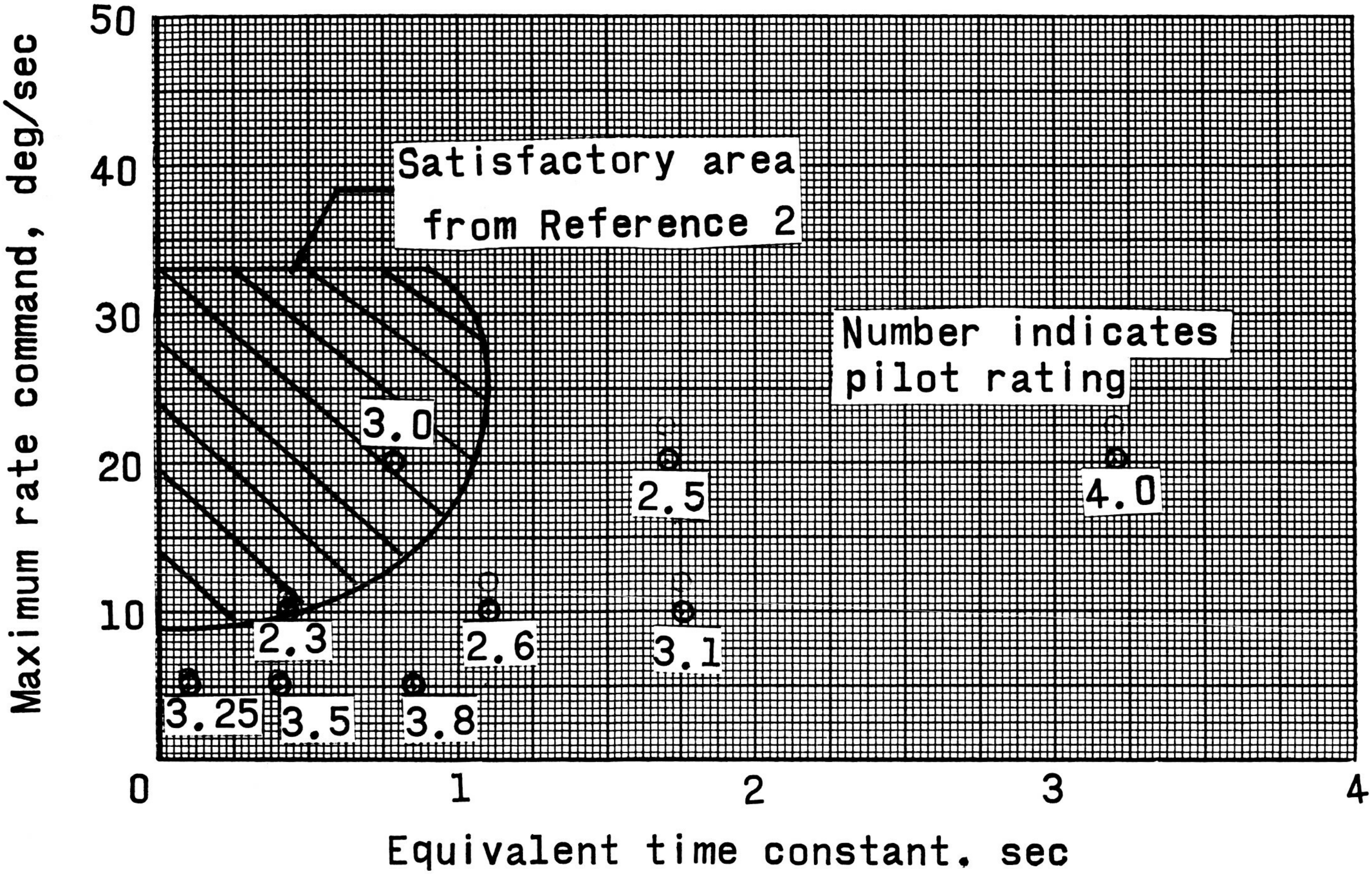
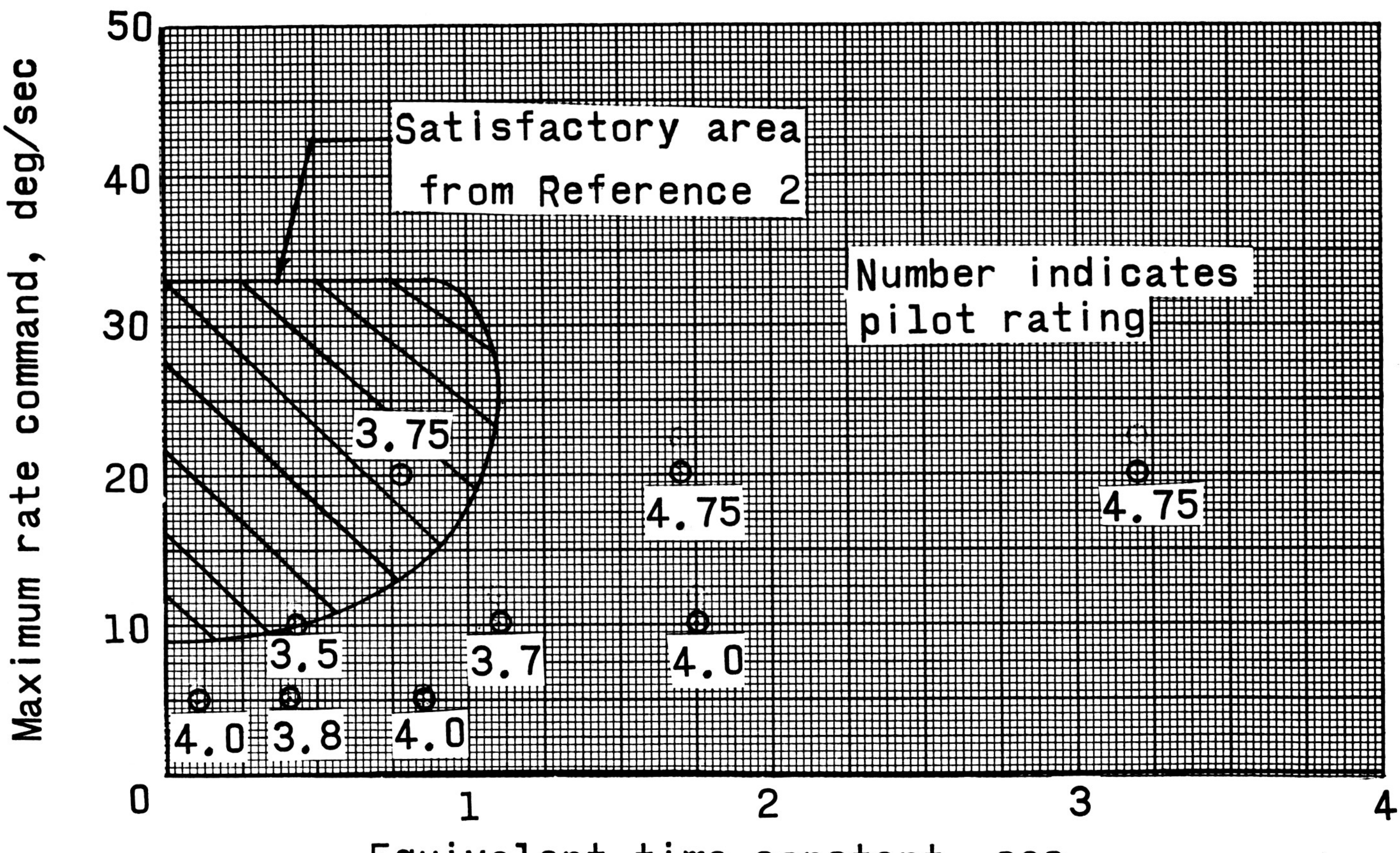


Figure 14.- Variation in attitude fuel consumption as a function of control jet size for an attitude command system.



(a) 0.25 deg/sec deadband.

Figure 15.- Comparison of pilot rating for on-off system with pilot rating of Ref. 2.



(b) One deg/sec deadband.

Figure 15.- Concluded.

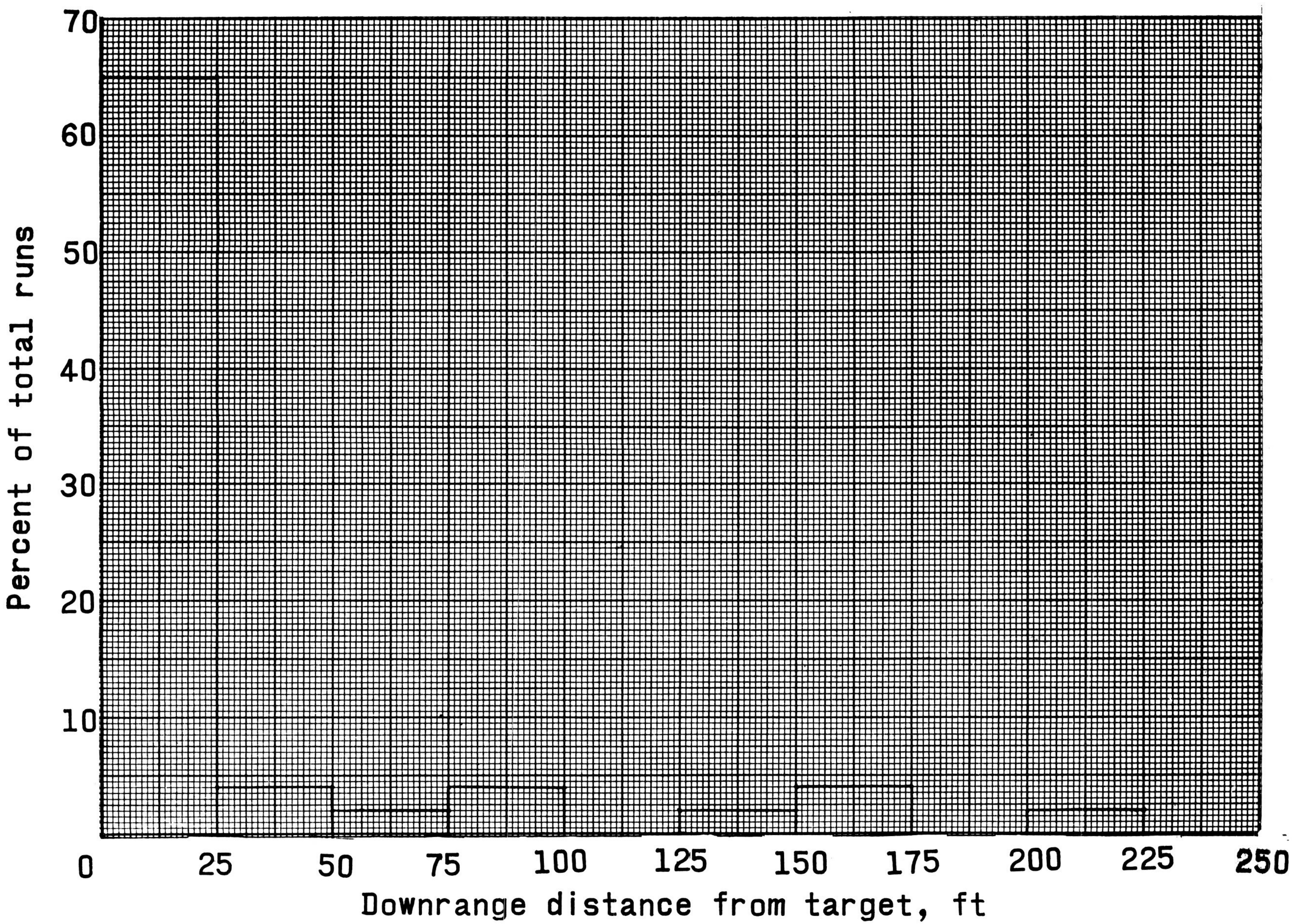


Figure 16.- Pilot performance, downrange displacement at touchdown.

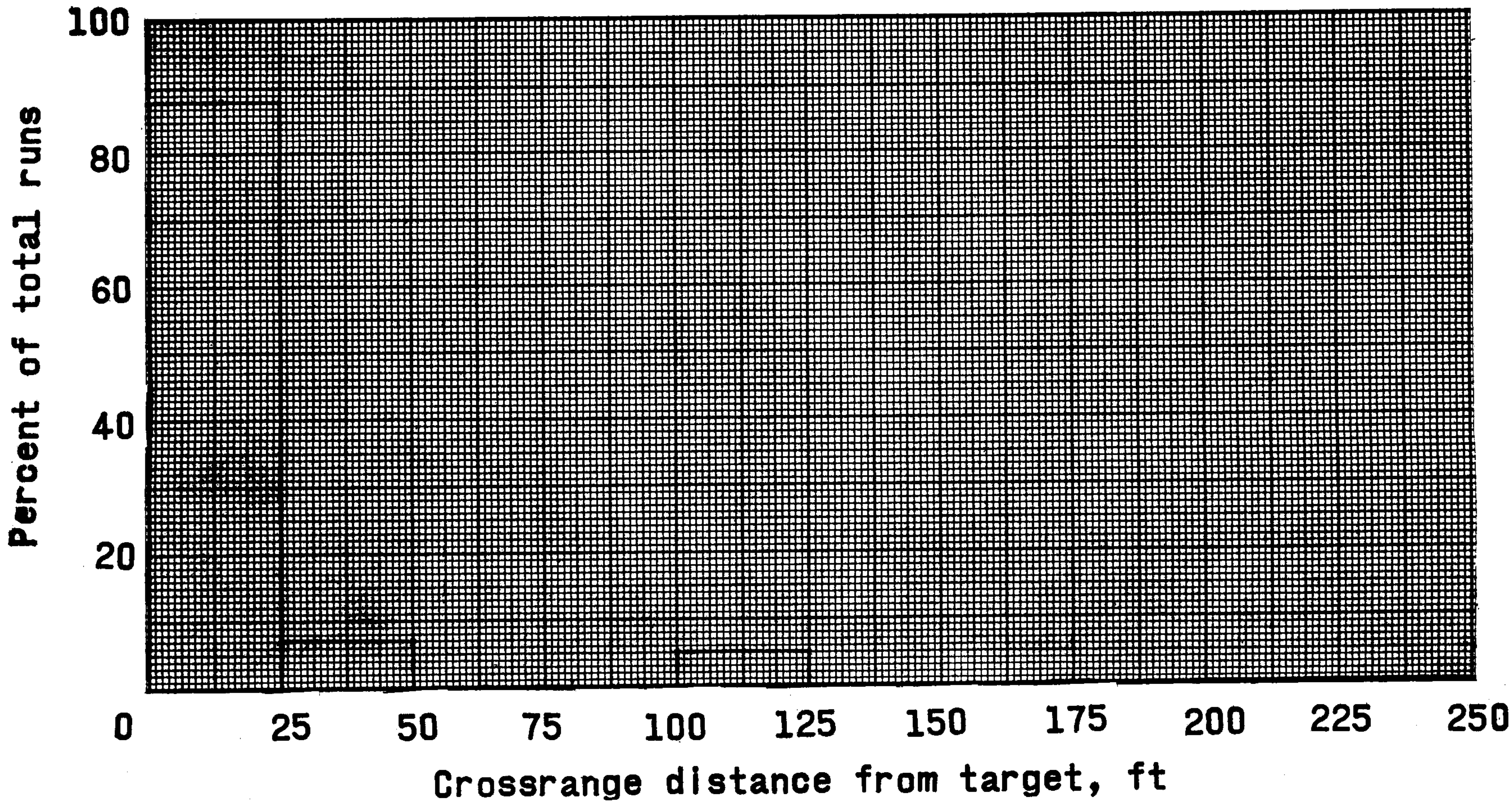


Figure 17.- Pilot performance, crossrange displacement at touchdown.

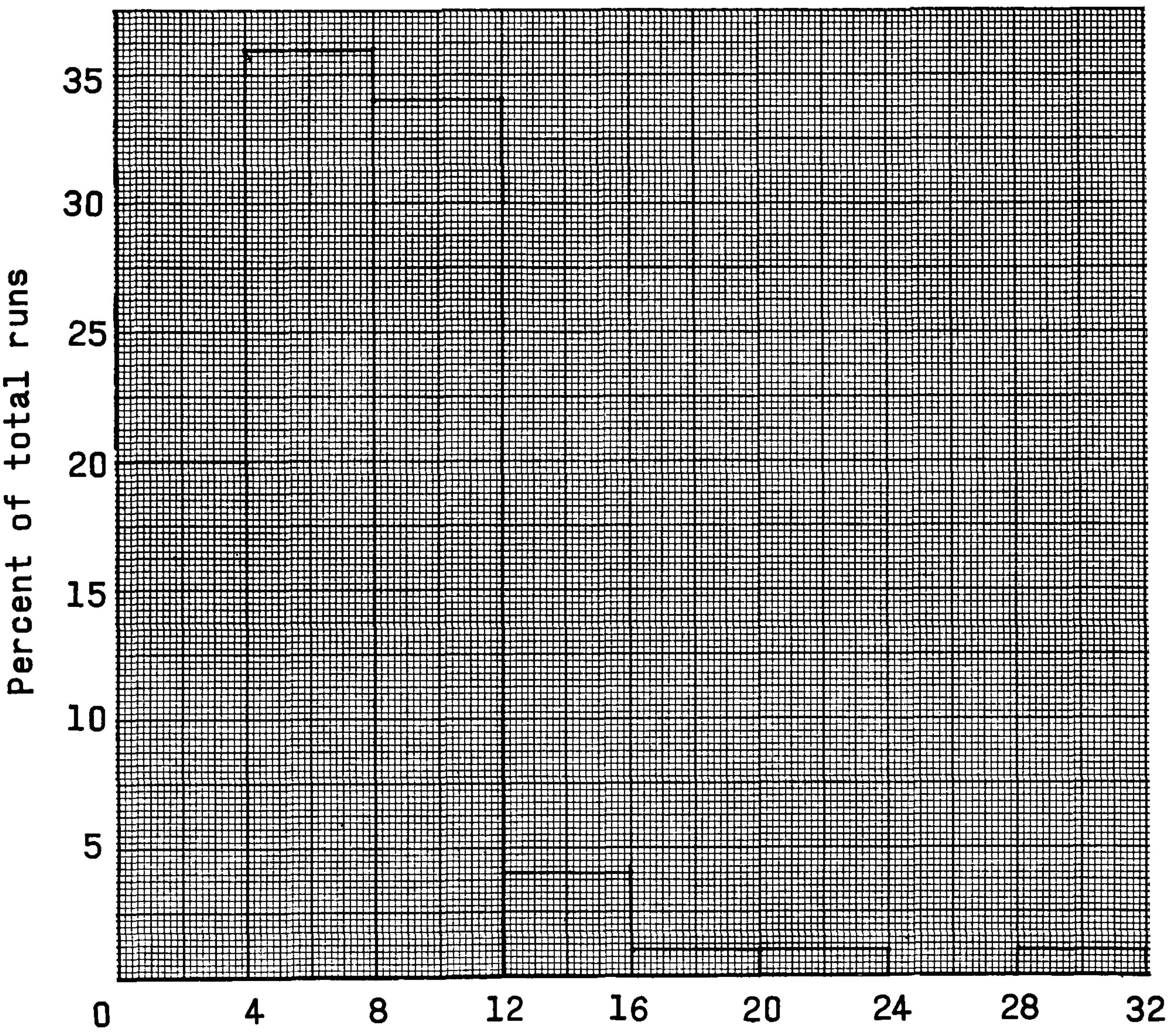


Figure 18.- Pilot performance, altitude rate of touchdown.

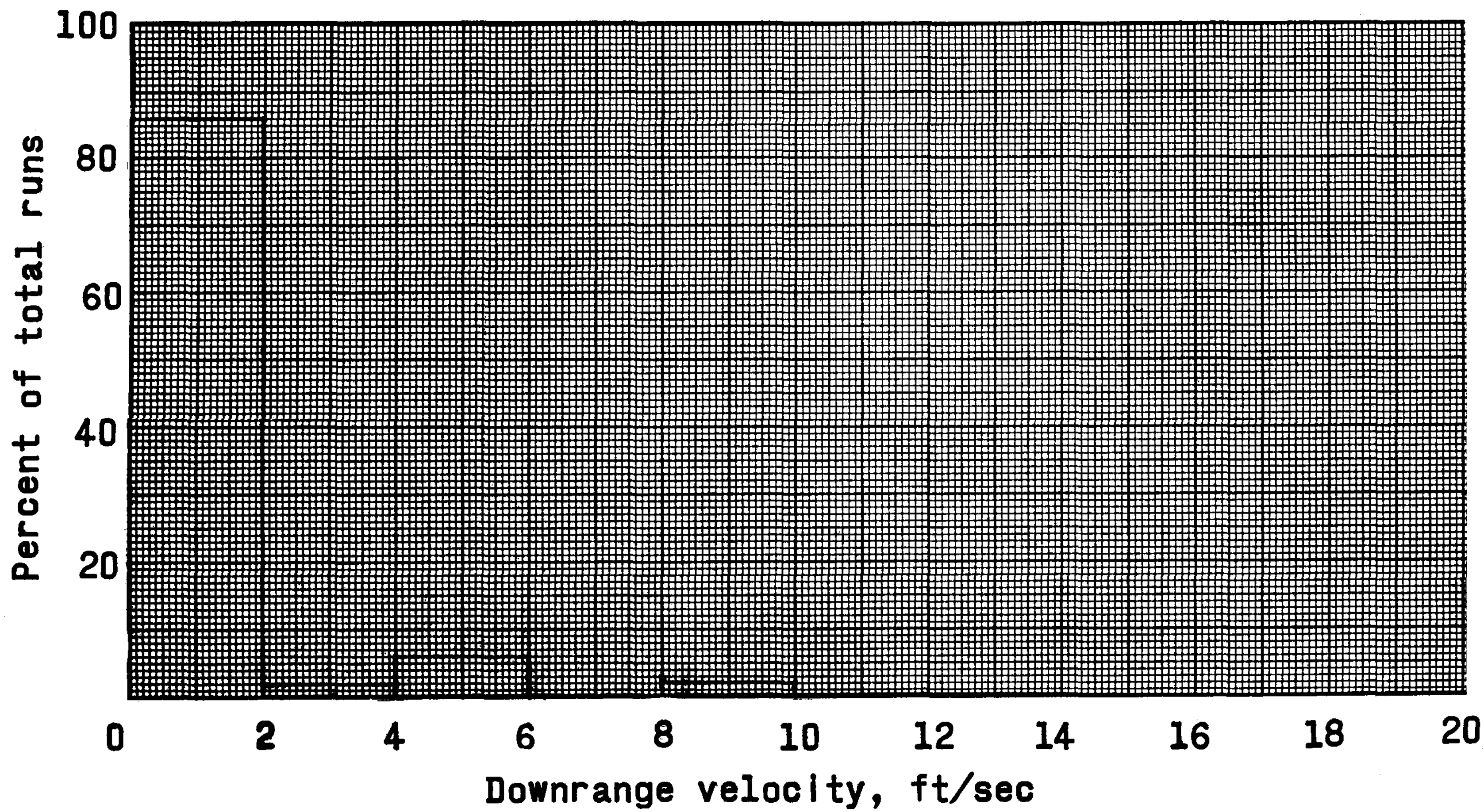


Figure 19.- Pilot performance, downrange velocity at touchdown.

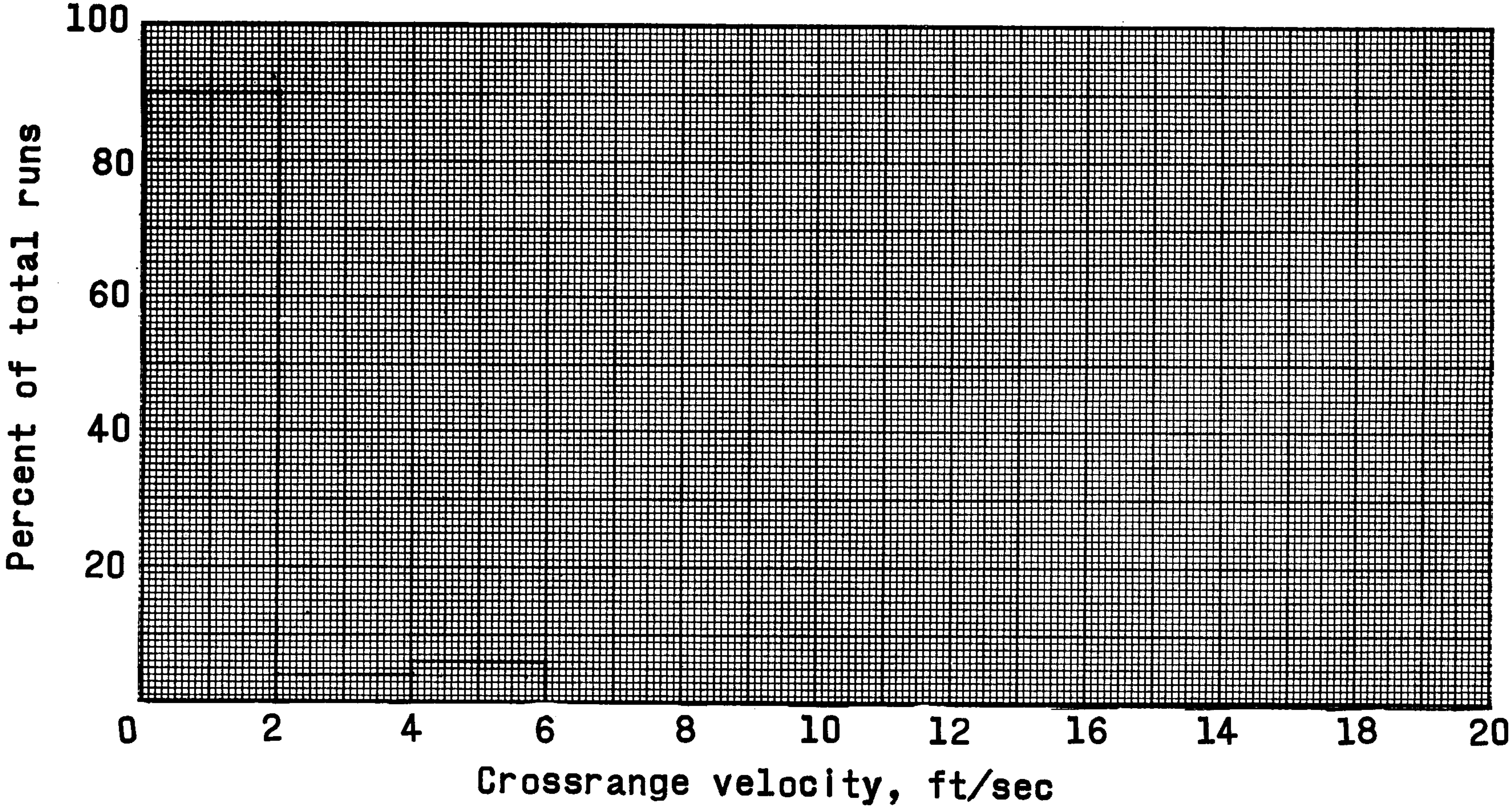


Figure 20.- Pilot performance, crossrange velocity at touchdown.

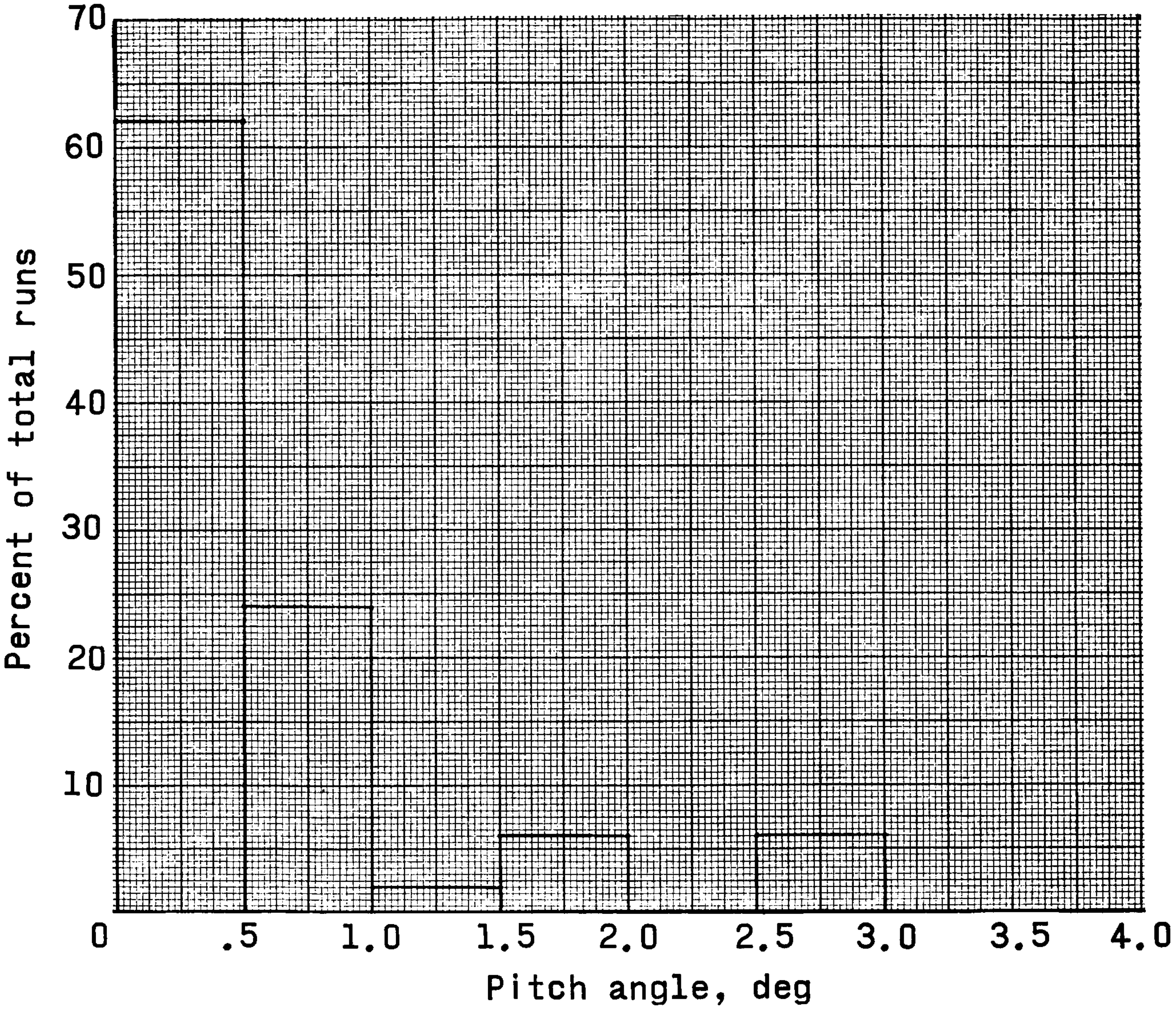


Figure 21.- Pilot performance, pitch angle at touchdown.

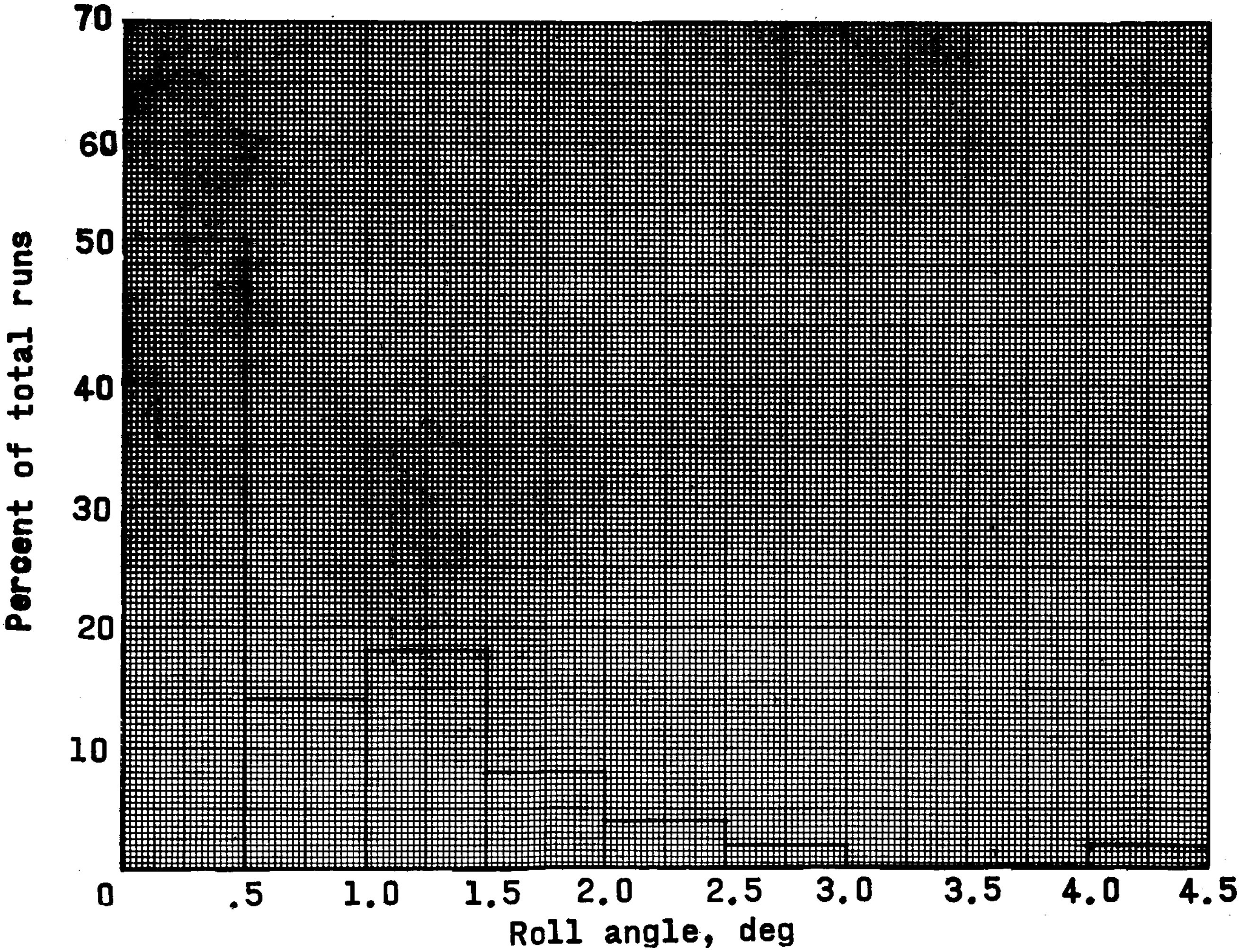


Figure 22.- Pilot performance, roll angle at touchdown.

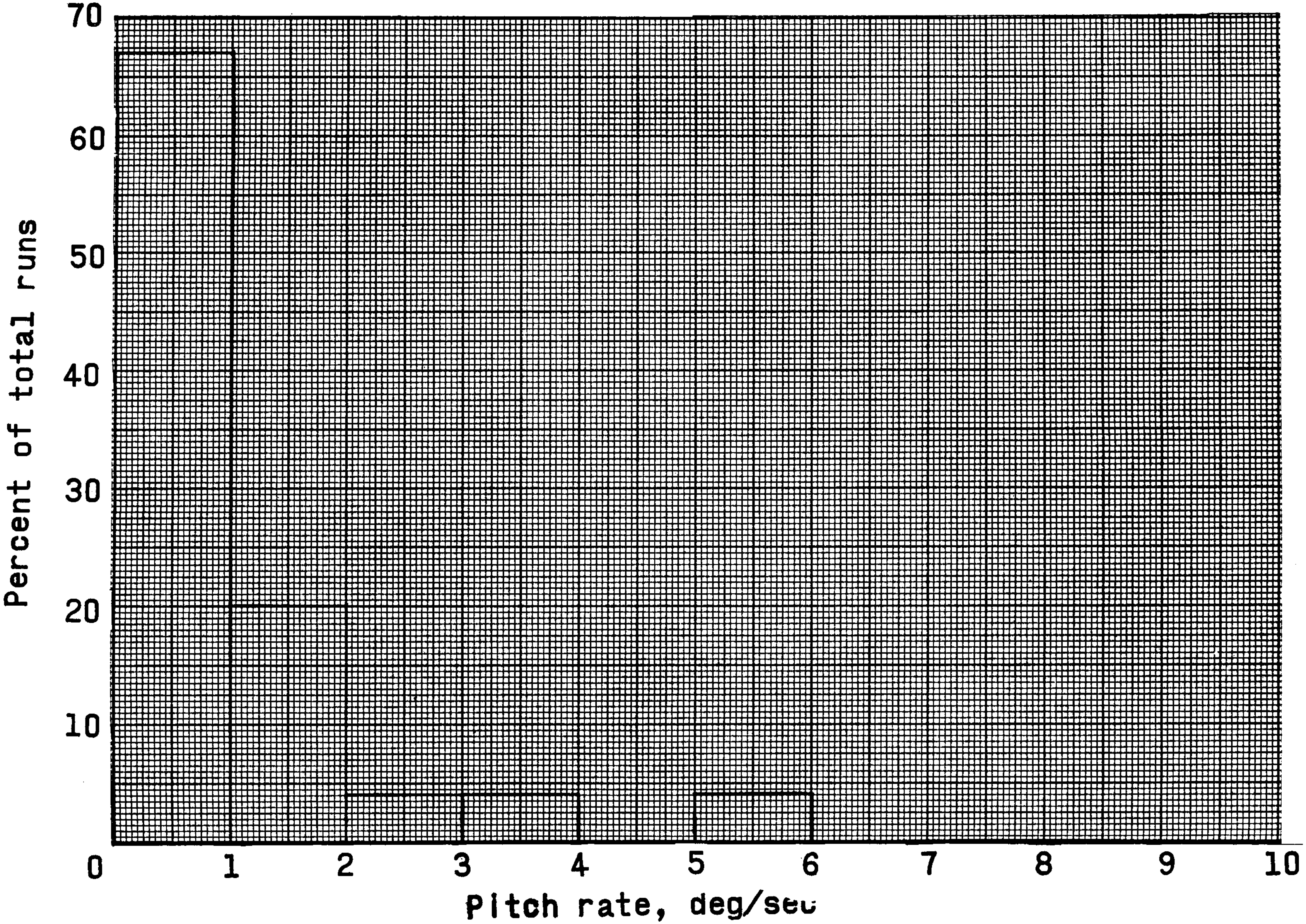


Figure 23.- Pilot performance, pitch rate at touchdown.

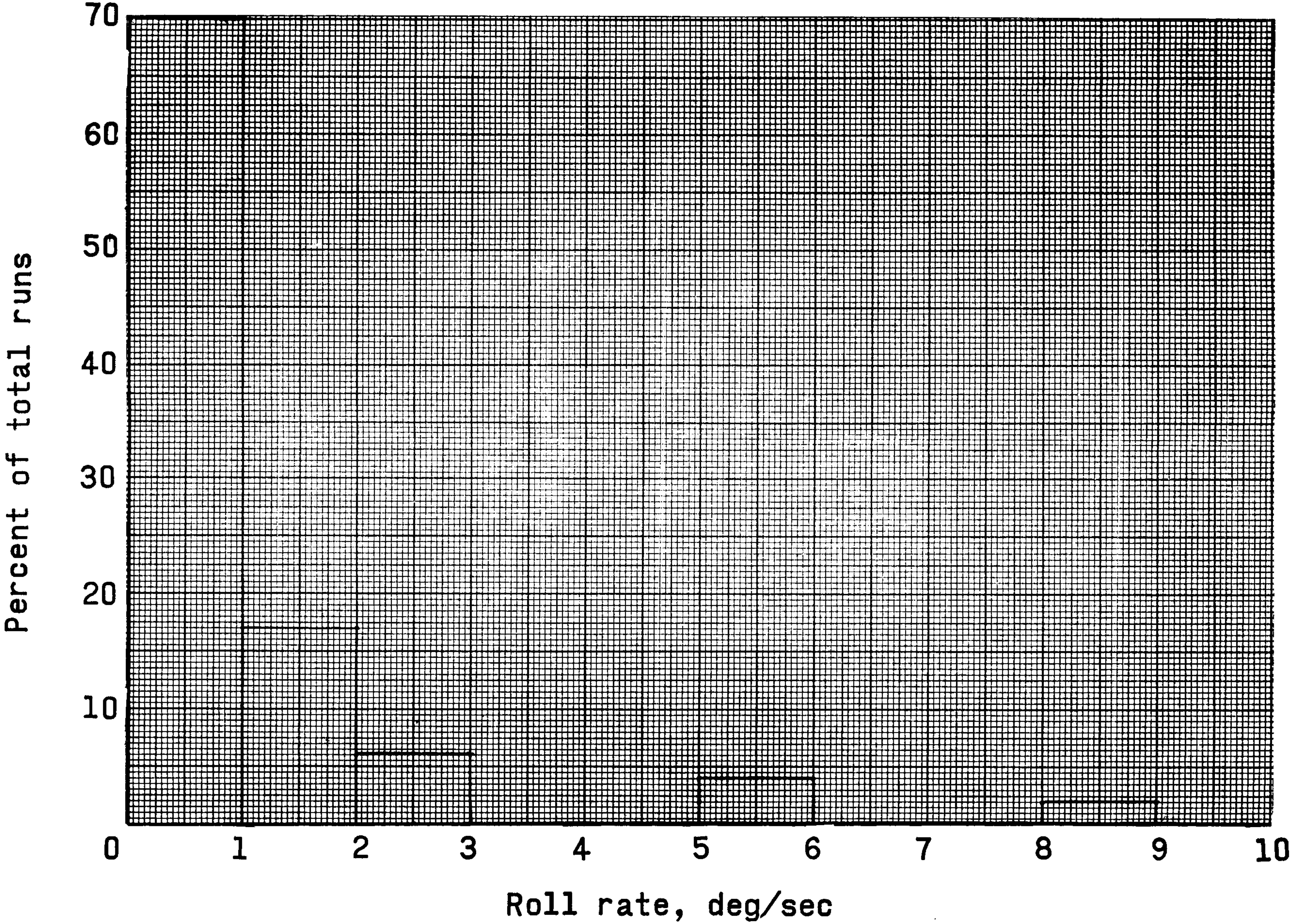


Figure 24.- Pilot performance, roll rate at touchdown.

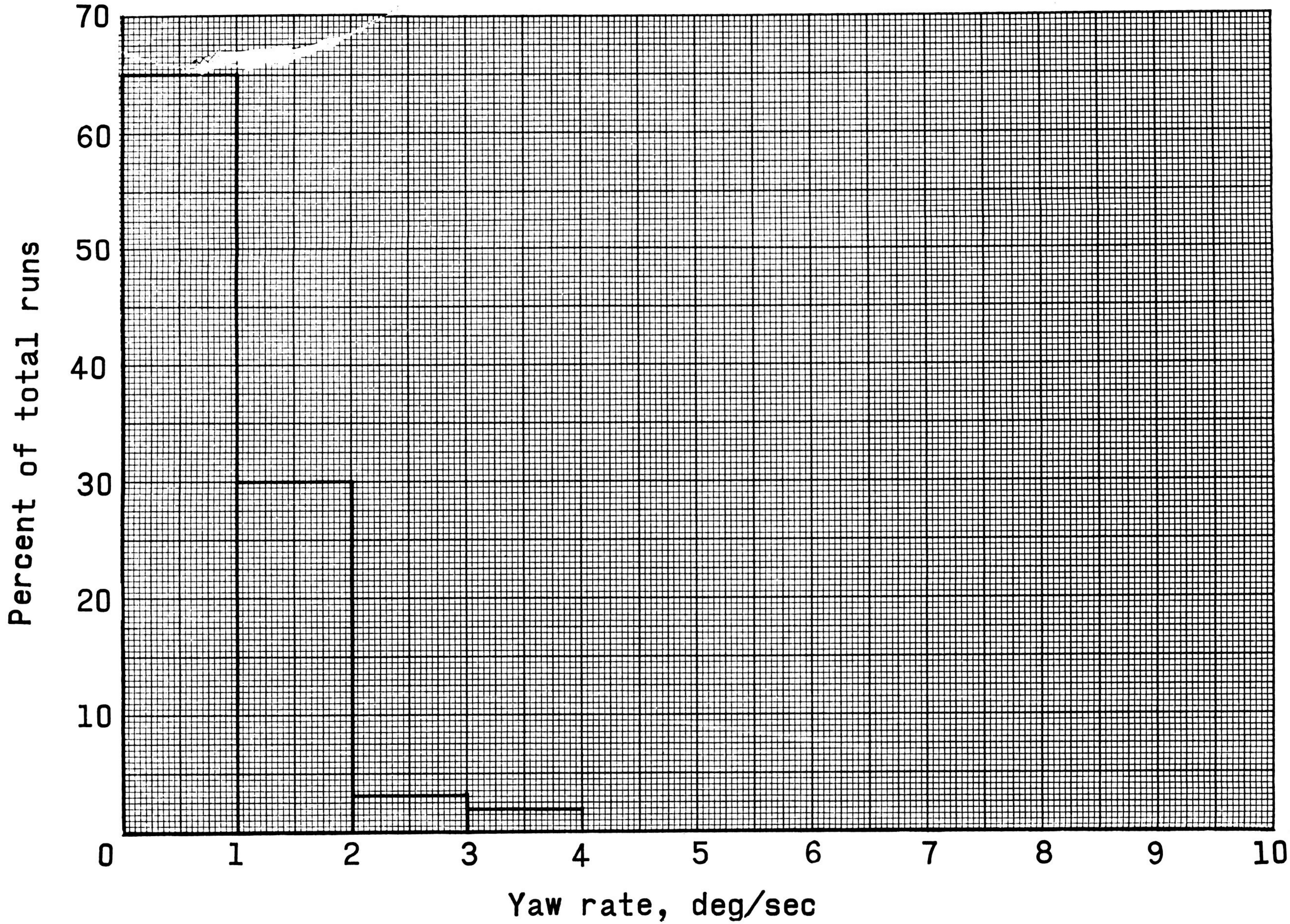


Figure 25.- Pilot performance, yaw rate at touchdown.